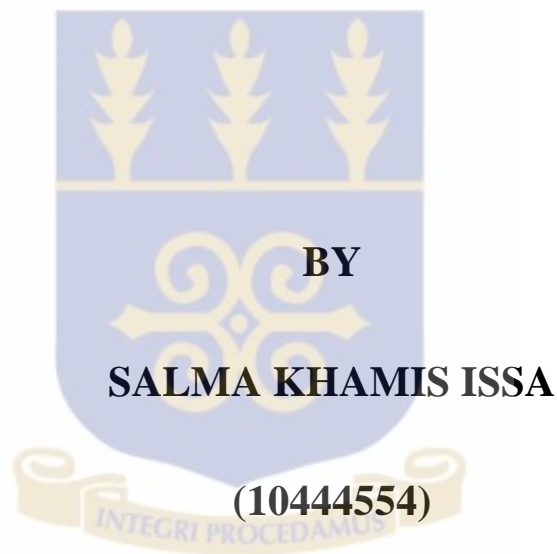


**OPTIMAL EXTRACTION OF NATURAL GAS IN  
TANZANIA: EMPIRICAL TEST OF HOTELLING'S  
PRINCIPLE.**



**A THESIS SUBMITTED TO THE DEPARTMENT OF ECONOMICS,  
UNIVERSITY OF GHANA, LEGON IN PARTIAL FULFILLMENT OF  
THE REQUIREMENT FOR THE AWARD OF MASTER OF  
PHILOSOPHY (MPHIL) DEGREE IN ECONOMICS**

**JULY, 2015.**

## DECLARATION

This is to certify that this thesis is the result of research undertaken by **SALMA KHAMIS ISSA** towards the award of MPhil Economics in the Department of Economics, University of Ghana, Legon. I hereby declare that with exception of the references that have been duly acknowledged, this thesis is entirely my own work and that no part of it has been presented for another degree in this university or elsewhere.

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## ABSTRACT

*There are huge expectations that Tanzania's current natural gas discoveries and extraction would provide significant growth in the economy. However, there are no empirical studies conducted to provide the understanding of the potential and efficient resource extraction paths, shadow prices, cost components and behavior of gas extracting firms, whether firm's are operating in a manner predicted by Hotelling's theory and its dynamic optimality condition.*

*We use panel Feasible Generalized Least Squares (FGLS) method to estimate the extraction costs, test the Hotelling's principle and estimate the shadow price. Furthermore, we use Excel Solver spreadsheet to simulate dynamic optimal cost path at range of discount rates.*

*The result shows that the marginal cost is inversely related with the quantities extracted as stock of gas reserves diminishes. Similarly, taxes are inversely related to firm's cost of extraction. The average shadow price estimated is \$ 6.33 per million BTU which is closer to actual domestic price of natural gas. Hotelling's principle is rejected given the range of discount rates and it suggests that natural gas firms in Tanzania are operating at sub-optimal level and the resource is not extracted in a manner predicted by the theory. We also found that the optimal cost path is decreasing with increasing quantities extracted for Songo Songo and Mnazi Bay natural gas fields. However, the cost path is not economical when higher discount rates are simulated.*

*The study recommends on reviewing and examining other factors that affects extraction cost which might limit the attainment of dynamic optimal paths in gas operating firms. This should not be the choice of discount rates and tax levels only, but also issues like transfer pricing should be re-assessed. They might increase natural gas extraction costs and limit optimal extraction path in the country.*

**Keywords:** Tanzania, natural gas extraction, Hotelling's principle, shadow price, optimal path, FGLS, excel solver.

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Author takes full responsibility of all un-intentional errors, misrepresentations and omission found in this work.

## DEDICATION

This piece of academic work is humbly dedicated to my lovely mom Mwanaasha Issa, my family, my loved ones, my friends and colleagues for their prayers, care, love, immeasurable support and encouragement in diverse ways throughout my academic life.



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## LIST OF ABBREVIATIONS

<b>Abbreviation</b>	<b>Meaning</b>
3SLS	Three Stage Least Squares
ADF	Augmented Dickey-Fuller
AERC	African Economic Research Consortium
BP	British Petroleum
BG	British Group
BCF	Billion cubic feet
BTU	British Thermal Unit
CAMP	Capital Asset Model of Pricing
EIA	Energy Information Administration
EITI	Extractive Industries Transparency Initiative
EL	Exploration Licence
EWURA	Energy and Water Utilities Regulatory Authority
FDI	Foreign Direct Investment
FE	Fixed Effects
FGLS	Feasible Generalized Least Square
FYDP	Five Year Development Plan
GAMS	General Algebraic Modeling System
GDP	Gross Domestic Product
GLS	Generalized Least Square
GMM	Generalized Method of Moments
HVP	Hotelling Valuation Principle
KV	Kilo- Volts
KWh	Kilo Watts Hour
INCO	International Nickel Company
IMF	International Monetary Fund
IPS	Im-Pesaran-Shin

LNG	Liquefied Natural Gas
OLS	Ordinary Least Square
MEM	Ministry of Energy and Minerals
MMSCF	Million Metric Standard Cubic Feet
MW	Mega Watt
MWh	Mega Watt Hour
NBS	National Bureau of Statistics
NSGRP	National Strategy for Growth and Reduction of Poverty
NYMEX	New York Mercantile Exchange
RE	Random Effects
PSA	Production Sharing Agreement's
SSA	Sub-Saharan Africa
SUR	Seemingly Unrelated Regression
TANESCO	Tanzania Electricity Supply Company
TCF	Trillion cubic feet
TEITI-MSG	Tanzania Extractive Industries Transparency Initiatives- Multi-Stakeholders Working Group
TPDC	Tanzania Petroleum Development Corporation
TRA	Tanzania Revenue Authority
TZS	Tanzanian Shillings
UK	United Kingdom
USA	United States of America
USD	United States Dollars
URT	United Republic of Tanzania
WB	World Bank
WEO	World Economic Outlook
WTI	West Texas Intermediate

## **CHAPTER ONE**

### **INTRODUCTION**

#### **1.0 Background**

Worldwide, natural gas plays a vital role in energy production for various uses. Its uses vary from household's energy consumption to manufacturing sectors. It is a commercial energy resource which is environmentally friendly, reliable and is known for being a highly efficient source of power generation in many countries (Neumann and Hirschhausen, 2015). The share of natural gas in the global energy mix is projected to reach 25% in 2035, overtaking coal to become the second largest primary energy source after oil (WEO, 2012). Worldwide, proven gas reserves are estimated at around 6709.03 trillion cubic feet (tcf) (AEO, 2013). Globally, natural gas production grew by 1.1% on average in 2013, which is below the average of 2.5% over 10 years ago (BP Stat, 2014).

Natural gas is a fossil fuel like coal and oil. Natural gas contains a mixture of methane and small quantities of ethane, propane, butane and pentane. It can also contain other non-hydrocarbons components like oxygen, nitrogen and carbon dioxide. Natural gas can be in the form of dry or wet gas. Dry gas consists of pure methane with no hydrocarbons. Wet natural gas has significant hydrocarbon quantities. Natural gas is extracted and brought to the surface from the source rocks by drilling a hole connected with gas reservoirs underground [(AEO, 2013) and (Bujulu, 2012)].

The maximum benefits that will be attained from natural gas extraction and utilization can influence policy maker's decisions on the potential extraction path that should be followed over time. This is because resource stocks have an economic value and they are able to generate potential income to the economy (Lin and Zhang, 2011).

Since natural gas is an exhaustible resource, it is the interaction between the reserves constraint and future consumption profiles that determines the opportunity cost of gas and hence its various optimal extraction levels. Hotelling (1931); Dasgupta and Heal (1979) and Farzin (1985), presented a general methodology for efficient pricing and intertemporal allocation of natural gas resources. Farzin (1985) concentrated on the issue of simultaneous determination of gas prices that will be efficient in selecting an optimal mix of gas using projects with import substitutes and scarcity rents.

Scarcity rents serve as the economic value of the natural resource as well as the opportunity cost of extracting natural resources now or in the future. Other studies use the term scarcity rents as shadow price, Hotelling's rent, royalty, user cost, in-situ price and resource rent; Hotelling (1931) used "net price" to mean the same thing, (Pindyck, 1978); Farzin (1992, 1985); Slade and Thille, (2009). The study uses shadow price to mean the economic value and rate of appreciation of the natural resources. Shadow price can also be explained as asset price or value of natural resources that the resource producer owns due to resource scarcity. It serves as the economic measure of the resource in the economy.

Tanzania has discovered new gas fields that are projected to be significant enough to make the country a key player in the natural gas trade. The country is expected to export to the growing global gas markets (Ledesma, 2013).

Two natural gas fields have been developed and gas is being used as energy to replace oil in Tanzania. These two gas fields are Songo Songo in Kilwa district and Mnazi Bay in Mtwara region with total proved reserves of around 1 trillion cubic feet (tcf) equivalent to 1,000,000 million metric standard cubic feet (mmscf) and with a possibility of reaching 3 - 5 tcf. Up to the mid-2012, there were significant gas discoveries offshore and in deep

waters. These onshore and offshore gas discoveries have a combined reserve potential of about 51.5 tbc (Tanzania Petroleum Development Corporation, TPDC (2014a). Intensive exploration in the discovery blocks and others places are still ongoing. Currently, there are about 18 offshore and 5 onshore exploration companies operating in the country (TPDC, 2014). Apart from regional and international gas trading, natural gas is also expected to serve the domestic market.

The natural gas and electricity sector in Tanzania plays a key role in energy efficiency and economic growth. The sector contributes 2.2% and 1.9 % to Gross Domestic Product (GDP) at current price for the periods 2001 and 2012 respectively.

Revenues and profits that will be earned from natural gas will improve the natural gas sub-sector and promote growth of the economy While a major gas export project can create large fiscal revenues, natural gas is also part of the solution to the nation's energy crisis and is essential for stimulating private sector development, diversifying the economy and creating inclusive growth (Demierre *et al*, 2014).

Over time, it will be important to identify the optimal extraction possibilities given the resource base potential and the expected profitability. Technological progress as well as changes in reserve stock may stimulate efficiency in extraction, and hence reduce costs. The cost reduction will have significant impact on the supply and demand of the resource as well as the growth of the economy.

In exploiting a nonrenewable resource, discounting the future plays a crucial role in consumption and investment decisions (Gaitan *et al*, 2004). The optimal rate of gas extraction depends on the cost of extraction and the size of natural gas reserves that are discovered and yet to be discovered in the near future. This involves a choice of

efficient paths of gas extraction to maximize the gains for the private firms as well as for social welfare according to (Hotelling's, 1931) principle.

By simple definition, Hotelling Principle is about the rate of change of scarcity rent or shadow price; shadow price is one of the key factors that influence the supply and market prices for nonrenewable resources. The shadow price is usually not directly observable therefore it needs to be estimated. The basic Hotelling (1931) model predicts price to be rising at the rate of discount less the extraction costs of the resource, which is termed as inter-temporal efficiency condition. This condition requires that the real rate of return to a resource owner should equal the social discount rate (Perman *et al*, 2003). Nearly 70 years later, most studies have been focusing on the inter-temporal allocations of exhaustible resources and assessing Hotelling's (1931) framework on optimal extraction of different natural resources under different market situations. These studies done so far have brought varying results on Hotelling's rule empirical validity and its predictions [Farrow (1985); Miller and Upton (1985); Livernois (2009) and Lin *et al* (2008)].

### **1.1. Problem Statement**

New discoveries and on-going depletion of natural gas has become a subject of huge concern regarding current and future resource prices, considerations for resource current levels of extraction as well as intergenerational equity. As a result, there is growing body of studies that investigates the changing resource price levels and compares it with its scarcity value, while other studies debate on the empirical validity of Hotelling's rule and its prediction of the behavior of resource extracting firms and resource markets [Lin and Zhang (2011); La France and Black (1998) and Leinert (2013)].

Hotelling (1931) formalized the model that would ensure the optimal extraction of nonrenewable resources. When a resource is extracted, the central role is to examine how much should be extracted in each period, so as to maximize profit for the firms and to have a social optimal extraction that ensures resource sustainability. This is because the owner of the resource can decide either to extract resource now or in the future depending upon the inter-temporal profitability of the activity. Other studies extended the Hotelling's model and conducted empirical tests to examine if the model predictions are consistent with what is actually observed on behavior of resource markets on extraction of exhaustible resources. Other studies are in support of Hotelling's predictions and its dynamic optimality (Slade and Thille (1997); Watkins (1992); Chermak and Patrick (2001: 2007) and Caputo (2011), while others have rejected (Halvorsen and Smith (1991) and Young (1992) the theory's usefulness in describing and predicting resource prices and the behavior of firms in the extraction of nonrenewable resources.

Despite these enormous studies, researchers seem to have given little attention to Sub-Saharan Africa in this arena. Unfortunately, there are no empirical studies conducted to test the empirical relevance of Hotelling's rule for extractive sector in Tanzania. In this respect, it is essential for a country to test the theory's usefulness in estimating shadow and market prices as well as predicting behavior of natural gas extracting firms. Also examine the potential and efficient extraction paths for its natural resources, in particular natural gas. We specifically use natural gas resource in this study because, recently there are huge expectations in the country that the gas resource would attract more Foreign Direct investments, provide more local employment and resolve energy and power crisis. The empirical test of the theory would therefore provide the understanding of the resource

extraction path, shadow prices, cost and behavior of extracting firms and ascertain whether the gas firms are operating in a manner predicted by Hotelling's theory. In line with this gap, research questions which arise are;

## **1.2 Research Questions**

The study will seek to answer the following questions;

- What is the natural gas extraction cost and its shadow price?
- Is the behavior of resource producing firms consistent with Hotelling's theory and its dynamic optimality condition?
- What are the minimum natural gas extraction costs that would ensure economical and the optimal extraction path for each resource extracting firm in the country?

### **1.2.2 Research Hypothesis**

The study seeks to test the following null hypotheses:

- The behavior of natural gas extracting firms do not conform with Hotelling's dynamic optimality condition
- Natural gas extraction cost does not ensure economical path in the country.

## **1.3 Objectives of the Study**

### **1.3.1 General Objective**

Therefore the purpose of this study is to examine the dynamics in the optimal extraction paths for the natural gas resource in Tanzania, and conduct an empirical test of Hotelling's principle.

### **1.3.2 Specific Objectives**

Specifically the study aims:

1. To determine natural gas extraction costs and estimating the shadow price that would ensure the economically optimal path.
2. To test the empirical relevance of Hotelling's principle using a range of discount rates.
3. To examine the optimal extraction path of natural gas firms in Tanzania.

#### **1.4 Significance of the Study**

The study is significant in the following ways. First, since there are intensive explorations and ongoing gas discoveries in the country, it is important to determine the extraction paths and ascertain a shadow price that is a crucial component in determining, designing and fixing the market price of natural gas. Therefore, the results of the study would provide the observed value of shadow price that would influence fixing of the market price of the resource, ensures the optimal and sustainable way of resource extraction as well as government revenue.

Second, the intuition behind this work is to show optimal extraction path for natural resources in Tanzania. Since there few studies done on natural gas sub-sector in the country, this study makes significant contribution to the development of the energy sector and secondly value addition on the theme of Hotelling's rule and on methodological background. Practically, the model adopted in chapter four is further extended by this study to include other vital components such as royalties and corporate taxes which typically significant in determination of natural gas extraction cost and optimal path. Therefore study will serve as a reference to other scholarly works, academicians and other stakeholders.

Third, government vision is to ensure the equitable management and sustainable use of natural resources for social economic development (United Republic of Tanzania-URT,

2008). For intergenerational consideration, the economic agents through the social planner should make an optimal extraction decision and policies that focus on non-renewable resource conservation and avoid overexploitation when consuming each additional unit of the resource. Therefore, consuming additional unit today involves opportunity cost and value of the resource in the future. The study results are used to inform the policy makers on the optimal production and efficient paths of the resource that would ensure current and future benefits (intergenerational equity) through reinvestments of returns attained from resource in other forms of assets.

Therefore, study results offer insights to gas producing firms business feasibilities and resource sustainability as well as institutions on the optimal extraction costs. The study also expects to inform policies and country plans like natural gas policy, natural gas master plan and Tanzania Vision 2025 and Production Sharing Agreements (PSA).

### **1.5 Organization of the Study**

This thesis is organized in six chapters. The first chapter is an introduction to the study. Chapter two provides the necessary theoretical and empirical literature on the optimal extraction of exhaustible resources with special emphasis on empirical relevance of Hotelling's Principle on different types of nonrenewable resources. Chapter three offers an overview of the Natural gas Subsector in Tanzania in relation to the extraction of this energy resource. Chapter four covers the methodology that was used in conducting this study in particular the use of Panel data technique for estimating the model and Excel Solver for optimization. The fifth chapter presents the empirical analysis of the study. Chapter six provides the study findings, conclusions and policy recommendations.

## CHAPTER TWO

### LITERATURE REVIEW

#### 2.0 Introduction

This chapter presents a literature review on the optimal extraction of non-renewable resources and basic theory of Hotelling's rule. Section 2.1 provides theoretical literature review related to the economics of nonrenewable resources. Section 2.2 focuses on empirical literature. Section 2.3 highlights literature on optimization process and the use of excel spreadsheet Solver and lastly, section 2.4 presents the conclusion of this chapter.

#### 2.1 Theoretical Literature

Literature dealing with the Economics of nonrenewable resources is essentially anchored on two broad perspectives. First, is the early fundamental theorem of Hotelling (1931) rule. And the second, empirical test of Hotelling rule.

Gaitan *et al* (2004) ascertains that, Hotelling's rule has become the pillar of the theory of nonrenewable resource economics. Since then, it has provided the fundamental insight into the long-run behavior of the prices, markets and the extraction rates for nonrenewable resources.

According to Hotelling's (1931) rule, "the price of a nonrenewable resource will rise at the rate of discount" in an efficient market equilibrium. Thus, the resource producer's optimal nonrenewable resource extraction problem is to choose the extraction profile that will maximize the present discounted value of the stream of per period net benefits. Assuming per period, net benefits from extracting stock quantity at a time (t), the social and private discount rates are the same, the initial stock of reserve is known and there are no externalities, then the social planner's optimal control problem of finding the maximum

benefit to the society, yields the same solution as it would arise in perfect competition (Zhang and Lin (2011), Permen *et al* (2003)).

The Hotelling's efficiency rule and dynamic optimality conditions that provide the theoretical structure for optimal extraction of nonrenewable under competitive market situation can be specified as follows:

Assuming extraction cost is zero, price of nonrenewable resource rises at the rate of discount  $\rho$ , when we are maximizing social welfare. Thus, the proportion of resource price will rise at the rate of discount over time.

$$\frac{\dot{p}(t)}{p(t)} = \rho \dots\dots\dots (2.1)$$

Where;  $P_{(t)}$  net prices of the resource over time,  $\rho$  are the discount rate.

Assuming resource extraction costs is not zero, then the optimal path according to Hotelling's rule, can be obtained by subtracting marginal cost of extraction from gross price. And hence the price of nonrenewable resource will be rising at the level of discount rate.

$$P_{(t)} - Cq'_{(t)} = \rho \dots\dots\dots (2.2)$$

Where,  $Cq'_{(t)}$  is the marginal cost of extraction,  $\rho$  is the discount rate and  $P_{(t)}$  is the gross price.

Studies by Perman *et al* (2003), Lin (2007) Dasgupta and Heal (1974) Pindyck (1978) justified that, Hotelling's rule holds, regardless of whether the resource stock is owned by a monopoly or a perfectly competitive firm. Under Hotelling's theory, resource owners seek to maximize the present value of net benefits obtained from extracting the resource, given consumer demand for the resource and subject to the constraint that total extraction

cannot exceed the initial resource stock. The optimal extraction decisions for each period in the production horizon are independent, since a unit of resource extracted today is unavailable for extraction in the future. The extraction paths between monopoly and perfect competitive market differs given the rate of discount, extraction costs, changes in demand and other uncertainties. Thus, in the absence of externalities, a perfectly competitive market maximizes a total utility, or what Hotelling (1931) termed as the Social value of the resource (Weitzman, 2003).

Solow and Wan (1976) have analyzed a situation where resource reserves differ in quality and the unit extraction cost increases as higher-grade reserves are exhausted; hence firms extracts lower grade reserves first. In their study, they demonstrated that along the optimal path, the shadow price of a resource must rise at the real rate of discount, despite differences in extraction costs. But the difference between price and marginal cost of extraction would decline monotonically to zero over time.

However, the literature contains sharply contrasting views on the subject of optimal extraction paths, especially on the empirical validity, testing and evidence of the Hotelling (1931) rule. Hotelling's rule has been revisited and modified by many researchers like Lin (2007), Krautkammer (1998) Farzin (1992), Lasserre (1991), Dasgupta and Heal (1979), Heaps (1985) and Burness (1976). The modifications incorporated other additional components in the model which were significant in explaining and supporting the rule empirically. Among the components incorporated are exploration and production costs, technological change, change in resource prices, effects on new discoveries, degradation effects, taxes, risks and uncertainties. The basic Hotelling's rule (1931) has remained the underlying theoretical and conceptual framework for understanding markets and the

optimal extraction path of nonrenewable resources (Livernois, 2009) despite being revisited by other studies.

In their study about the optimal depletion of an exhaustible resource in a dynamic general equilibrium model, Gaitan *et al* (2004) has questioned the validity of Hotelling's rule. They argue that, the Hotelling rule as the fundamental theorem of nonrenewable resources is limited by its partial equilibrium nature and needs to be extended into general equilibrium nature. One symptom of this inadequacy, was due to a disagreement between the empirical evidence showing stable or declining resources prices and nature of the rule in predicting increasing prices exponentially.

The shadow price is the rate of appreciation of the natural resources and sometimes it serve as the economic measure of resource scarcity.

Farzin, (1992) undertook a study on the time path of scarcity rent on exhaustible resources; he asserted that the shadow price is unknown and hence the predicted path of market price for nonrenewable resources will also be unknown. In contrast, Krulce (1993), concluded that the shadow price rises over time as the resource is extracted. Due to these opposing results on the trend of the shadow price and hence market price for the nonrenewable resource, Livernois and Martin (2001) concluded that, if an extraction cost function conforms with established conditions, then the shadow price will definitely increase. However, due to one's set of established conditions, there is no assurance that the predicted shadow price will steadily rise. Therefore, it further creates difficulties in empirical testing to give profound evidence in support of Hotelling framework, (Livernois, 2009).

The assumption of an inverse relationship between extraction costs and the size of the reserve base is of great importance in models that form the literature on nonrenewable resource economics. This assumption appears on the models of exploration and extraction developed by {Pindyck (1970, 1978), Devarajan and Fisher (1982), and Lasserre (1985) Livernois and Uhler (1987),}

Livernois and Uhler (1987) explained that the main incentive for exploration is searching for new un-depleted reserves to offset the rise in aggregate extraction costs brought about by extraction of existing reserves. They indicated that extraction costs will tend to rise as reserves in a single deposit are depleted. In the beginning, reserve base is treated as a single large deposit, if the reserves are smaller, then higher extraction costs would be realized. Inversely, extraction costs become lower, if the reserve base happens to be larger (Pindyck, 1978). Resources which have lower extraction costs tend to be mined first.

Lin and Zhang (2011) explained stock effects as the dependence of extraction cost on the stock of reserve that remains on the ground. The dependence of remaining reserves on the ground is inversely related to extraction costs. There are possible reasons as to why this dependence is inverse. One of the reasons is that, if the kind of resource needed is to be extracted from greater depths, and then extraction costs may increase as more of the reserves are extracted and less remains on the ground. Also, extraction costs may increase if a well's pressure of oil or natural gas declined over time as more of the reserves are depleted. They pointed out that different grades of a resource may differ in their extraction costs, and since the cheaper grades are more likely to be mined to exhaustion before more expensive grades are mined, then the cost of extraction may also increase as the cheaper grades are exhausted.

Pindyck (1978) in his study of assessing the behavior of firms under optimal exploration and production, explained the typical exhaustible resource problem for competitive and monopoly markets. Under competitive markets, the price rises slowly over time as reserves are depleted. He also pointed out that, unless extraction costs are zero and the elasticity of demand is constant, in each case, both price and exploratory activity to maintain the level of reserves will be the same for monopolist and the perfect competitor. However, before Pindyck illustration, Stiglitz (1976) showed that, in the case of production without prior exploration activity, to increase the level of reserves, the conditions of zero extraction cost and constant elasticity of demand may result in monopolistic and competitive trajectories that are identical. Pindyck concluded that the optimal level of building and maintaining the reserves is highly dependent on the initial levels of reserve endowments and the rates of resource extraction. If the initial reserves are smaller, then the price profile for the resource will not follow increasing rates as in Hotelling's rule but will rather stick to U-shaped price path.

According to Pindyck (1978), the U-Shaped price path for nonrenewable resources can be described in two cases. The first case of the U-shaped price path might happen if reserves are initially very small price, and exploration will begin declining from a higher level. Therefore, as reserves are depleted, the price will increase until demand, exploratory activity, and the profit on the last extracted unit of the resource becomes zero simultaneously. Then it means the optimal trajectory depends upon costs of extraction. The second case of the U-shaped price path can be explained as; if the extraction costs are small, exploration activity will show a fluctuating trend as it declines, rises and declines again. As production increases, the firm will do more exploration so that the stock of

reserves is maintained. In the end, the exploration will decline which will give less returns, increasing extraction costs and hence exploration will fall to zero since extraction costs depends highly on the level reserves.

## **2.2 Empirical Literature**

Barnet and Morse (1963), are among the earliest researchers who conducted an empirical study of the time path to examine the proposition of increasing economic scarcity of natural resources. They concentrated on the issue of extraction cost. They graphed the product price data for minerals, agriculture, forestry and commercial fisheries from the United States for the period 1870 to 1958 and found that the price trend was approximately horizontal. Their aim was not to test the relevance of Hotelling's model as such, but look at the premise of increasing scarcity of natural resources when the economy grows. The results found that unit costs showed a decline for minerals, commercial fisheries and agricultural sectors, whereas unit cost showed an increase for the forestry sector. They concluded that, the data used for that period did not support any increasing resource scarcity.

However, Smith (1979) conducted an econometric study to evaluate the Hotelling model and re-evaluated Barnet and Morse (1963) conclusion. Smith failed to indicate any consistent upward trend in the prices of natural resources. He indicated that the trend in mineral prices was negative with the rate of decline and real prices were decreasing over time in absolute magnitude for the period 1900 to 1973.

Heal and Barrow (1980), attempted to test the empirical validity of the theory of exhaustible resources with the price of the resource (shadow price) as a variable of interest. The time series data was examined for the period from 1965-1977 in return for copper, tin,

lead and zinc. The model used was explicitly linked asset arbitrage and capital assets of the resource. Heal and Barrow estimated a reduced form equation of supply and demand for the flow of resource which was a function of income, resource price and return on the resource relative to return on other assets. Restricted and unrestricted transformed equations were specified and employed OLS techniques to obtain their estimated results. Interest levels were found to be significantly related to metal prices. They found that resource price movements are highly related to the rate of interest rate changes rather than being a function of discount rate levels as predicted by Hotelling's principle. However, the empirical study failed to reject the Hotelling's framework.

Some empirical studies have found evidence for a U-shaped price path. In a study that aimed at analyzing long run relative price movements of nonrenewable commodities, Slade (1982) explained that from eleven major metals and fuels, the predicted price paths for these nonrenewable resources were U-shaped. The time series annual data from 1870 to 1978 seemed to be consistent with Hotelling's Rule. She explained that, after substantial initial declines of prices in the 1960's there was some evidence of an up-turn in the real-price paths of many mineral commodities in 1970's. She used to fit linear trends and fitted quadratic trend models for econometric estimations. With the fitted linear trends model employed, there was no evidence of natural resource scarcity but for the fitted quadratic trend models, the prices initially fell but later rose. Hence, she concluded that, nonrenewable resources are becoming scarce if scarcity is to be measured by relative prices.

Other studies in support of *U*-shaped price paths and hence the consistency of Hotelling's model are (Livernois and Uhler (1987) and Swierzbinski and Mendelshohn (1989). They

explained that when exploration of new reserves is added to the basic Hotelling model, then the extraction and production of the resource can lead to a U- shaped price path.

Stollery (1983) undertook a study to test the Hotelling's rule using time series estimates of shadow prices of nickel. He extended the basic Hotelling model and included technological change, effects of depletion and present and future reserve discoveries. Using Price leadership model with the International Nickel Company (INCO) as a leader, the annual data from 1952 to 1973 was collected to estimate a log linear demand function and Cobb-Douglas production function. Employing a Capital asset pricing model (CAMP)<sup>1</sup> with estimated discount rate of 15%, the estimated time path of the shadow prices for nickel was positive and consistent with the predicted time path of Hotelling Rule. Hence Stollery revealed that, the shadow price rose overtime, which would also make the market price of nickel to perform the same.

Miller and Upton (1985) looked at another reduced form of Hotelling model which was termed as "Hotelling Valuation Principle" (HVP). This principle states, "the value of a unit of reserves in the ground will be the same as its current value above the ground, when marginal cost of extraction is subtracted from it". They used data on U.S domestic oil and gas producing companies to test implication of HVP from December 1979 to August 1981. They defined Hotelling's model in terms of the asset value of the domestic oil and gas companies and regressed the market values of the reserves on their Hotelling's values. The HVP was tested using pooled cross sectional tests and the analysis was done using Ordinary Least Square (OLS), Maximum Likelihood and Davidson- MacKinnon test

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<sup>1</sup> Capital Asset Pricing Model (CAMP) is used to calculate the required rate of return for any risk type asset. Is the equilibrium model for portfolio analysis where by the assets under high demand will realize higher prices and hence yield higher expected returns (Sigman,2005)

(1981). The results found the net prices equal with estimated oil and gas reserves when a sample of companies were compared. Also econometric analysis failed to verify that the net price of resource must rise at the rate of discount as stated by Hotelling (1931) and restated by Dasgupta and Heal (1974). Hence, on the HVP, the current net price will define all future prices given the rate of discount. They concluded that, the relation of the market value of resources to current net prices appeared to conform closely to HVP.

Farrow (1985), conducted an empirical study to test for consistency between the theoretical basis, privately efficient extraction path and actual extraction path of a firm. His study included empirical tests of the dynamic efficiency conditions of the Hotelling model under perfect competition. The data used to be on monthly basis from 1975 to 1981 supplied by mining firms under hard rock mining industry which extracts several metals from ore. Farrow specified Trans-log cost function and he used three empirical models of dynamic efficiency to test the Hotelling's model. Basically, OLS was applied to estimate parameters of the basic model and a stochastic model for dynamic efficiency was later used for estimation. The empirical results reject the basic Hotelling hypothesis for the data and firm's behavior aside. He concluded that, Hotelling's model is insufficiently strong to be applied to empirical issues.

In his study, Watkins (1992) reviewed the Hotelling principle and provided new empirical results based on the transaction values of oil and gas reserves. He discussed the changes in ultimate reserves by reviewing Canadian natural gas base over time and evaluating this change by drawing special attention to the work done by Adelman (1990). The data were collected on a monthly basis for 27 Canadian oil and gas reserves' transaction and value from 1989 to 1991. OLS estimation techniques were employed. He also examined how

Hotelling's model was adopted in Canada as one of the regulatory tools and evaluated the appeal for natural gas exports. He concluded that the reserve transaction data provide no expectation that the net price would rise at the rate of discount as it was stated by Hotelling's model. Also, the Hotelling's rule just yields theoretical insights but was not found to cope with oil and gas sectoral realities in Canada.

Halvorsen and Smith, (1991), undertook an empirical test of the Hotelling's rule (1931) on vertically integrated resource industries. They used Canadian metal mining industry time series data from 1954 to 1974. Duality theory was used to derive an econometric model and a Cobb-Douglas restricted cost was specified. An iterative three stage least square was employed in the econometric estimation. Hausman (1978) specification test was used to test the parametric restriction on the restricted cost function and in showing the implications of data to Hotelling's rule. They assumed constant and varying discount rates pegged to Canadian interest rates and the results suggest a slight upward trend in shadow price with growth rates of 0.57% and 0.38% respectively. They concluded that, for the Canadian metal industry, the empirical implications were strongly rejected with the Hotelling's framework and this rejection might be due to inadequate characterization of privately optimal behavior on the theoretical model postulated.

In his study, Young (1992) examined the costs behavior of the Panel of 14 Canadian copper mining firms to check if the firm's behavior is consistent with the basic Hotelling model. The annual time series data collected consisted of output, cost and other relevant variables from 1956 to 1982. He specified a cost function and performed the estimation of the Euler Equation through Generalized Method of Moments (GMM). The results from GMM estimates indicated that, there is a direct relationship between the form of cost

function used by a mine owner and the form of corresponding Euler equations in the resource owner's intertemporal profit maximization problem. He also found that, costs increases with copper production of more than 90%. He concluded that, the estimation did not show consistency with Hotelling Model, as also found by Farrow (1985).

Adelman and Watkins (1995) attempted to empirically test the Hotelling Valuation Principle (HVP) using data from 34 developed oil and gas reserves in Alberta. The data were collected on a monthly basis from 1989 to 1991. The Conventional cash flow budgeting approach for valuing mineral properties was underlined. The OLS regression technique was performed in a reduced form which derived growth rates in prices that underlie empirical results. The results indicated that, the implicit growth rates of prices for oil and gas are -3.6% and 5.8% respectively using 10% discount rate. Also, the results showed the estimated reserve values cannot be reconciled with HVP because the values were below the net wellhead prices. Although shadow price values provide valuable insights for the future prices of oil and gas, crude oil is different from natural gas in respect of well head price, shadow prices and costs, as their prices have been diverging significantly over time.

Slade and Thille (1997) conducted a test of the Hotelling's framework employing cost function estimated by Young (1992) for 14 Canadian copper mining firms. They derived and tested a model which unifies two strands of economic and financial literature. The models provided are basic Hotelling model and the Capital Asset Pricing Model (CAMP) of risky assets. The CAMP model, which was incorporated into dynamic efficiency condition of Hotelling's framework provides a relationship for the life of asset, rate of return on risky asset, the risk free rate of return and expected rate of return on the market

portfolio. The GMM estimation technique was used for dynamic panel data to obtain efficient estimates. They derived the shadow price, change in shadow price and marginal cost of remaining reserves. They later put some restrictions on the parameter estimates, and used Wald test to check for consistency with Hotelling rule. The estimated results of the test failed to reject the Hotelling / CAMP model.

Chermak and Patrick (2001), conducted an empirical test of the theory of exhaustible resources (Hotelling model) on Canadian firms extracting natural gas. The data were collected on a monthly basis for five years from 1987 to 1991 and comprised of 443 observations from 29 gas wells. Duality theory was used to derive an econometric model and they specified the indirect cost functions in a form of a generalized Cobb- Douglas function. Four cost functions were specified, namely restricted, unrestricted, average and gross cost functions and were econometrically estimated using panel linear regression of Feasible Generalized Least Square (FGLS) technique. The shadow price was estimated using restricted cost function. The Hotelling's model dynamic optimality condition was tested using Hausman (1978) test, with different cost function specification, using derived propositions together with discount rate ranges. The results found the shadow price for natural gas ranges from \$ 0.000001 to \$ 0.858 per million cubic feet (mcf) for all natural gas wells. They concluded that, the empirical test and data indicates the theory is useful in unfolding the behavior of independent resource firms and hence failed to reject Hotelling's framework.

Lin and Wagner (2007) combined stock effects and technological progress to develop a theoretical Hotelling model. They explained that the Hotelling's framework in steady state has been consistent with the often cited stylized facts. They pointed out that, mineral prices

have remained constant over a long period of time (Slade, 1982) or under certain conditions prices. Empirical investigation of their model was conducted using data for 14 various mineral prices and extraction costs from 1970 to 2004. They also tested the hypothesis that stocks degradation effects and the effects of technological improvements offset one another. They performed OLS, Seemingly Unrelated Regression (SUR), fixed effects and later employed three stage least squares (3SLS) for econometric estimation. The results found to have a balanced price growth path and the prices for 13 of the 14 minerals revealed a zero growth rate over a 35 year period. Also, they concluded by validating their derived steady state Hotelling's model for about 8 out of 14 minerals.

In his study, Livernois (2009), attempted to show the empirical significance of the famous Hotelling's (1931) model by reviewing previous empirical literature. He provided insights into what has been observed in the behavior of resource extracting firms and resource markets in the long run supplies and prices of resources. Livernois explained that technological innovation can change existing and future extraction costs as well as resource price. Unanticipated resource discoveries would have crucial downward effects on shadow price and hence market price for the resource. He simulated the price path of the Hotelling model over 100 periods. The results found the U-shaped price path of the kind obtained by Slade (1982). Livernois concluded that, Hotelling's rule continues to be the basic and vital feature, in understanding the behavior of resource markets in the economics of nonrenewable resources.

Lin (2009) calibrated Hotelling's model of optimal resource extraction, with unlimited potential reserves when costs exhibit stock effects. Her study used annual data on world oil prices and consumption for the years 1965-2006. She simulated model for both perfect

competition and monopoly with different specifications of demand elasticities. Lin used three measures of fit which are summary statistic comparison, Mean squared Error (MSE) and correlation to find the results that best fit the data. The results were that, the real oil price should fall in the range \$ 117-160 per barrel over 2000-2010 years; also the extraction rates should be constant at 59.8 million barrels per day over the simulation period of 1857-2300. She also pointed out that, the models used fit with actual data when oil market is perfectly competitive and demand is inelastic. Lin suggested that, one should augment the basic Hotelling model with other modifications like uncertainty, different cost functions and technological progress to test the model properly.

In their study, Hart and Spiro (2011) questioned the theoretical and policy research issue that shadow prices contributes a large proportion to the market price of nonrenewable such as oil and coal. They observed the coal and oil average prices for 1980-1989 and 2000-2009. They explained that under Hotelling's analysis, there are at least two basic reasons of either failing or constant resource prices. It might be that shadow price is well behaved, but masked by other factors; or the resource markets failed to value the natural resources in the ground, according to the theory's predictions. Back of the envelope numerical simulations for crude oil and coal were performed. The method aimed at illustrating necessary implication of a high shadow price, assuming resource costs change at a constant rate while shadow price rises at a constant rate as well. Oil reserves will run at a backstop price of 150 dollars/barrel in 2050 if there are higher levels of current shadow price. The study found that, historically, shadow price seems to have marginal and non-existing nature, hence it is not key in the determination of many nonrenewable resource prices that are seen currently. In addition, other factors are anticipated to shape, influence and dominate the

nonrenewable resource prices in future. The study concluded that, shadow price is not the only factor and basis for policy advice regarding the make-up of current and future nonrenewable resource prices. Principally, there are other considerable factors aside from the estimated shadow price that are vital in shaping the real resource prices.

Caputo (2011), undertook a study on the empirical test of the extended Hotelling theory. Classical and Bayesian statistical techniques were used to estimate the provided econometric model and hypothesis tests of the rule. Unbalanced panel dataset of nine Canadian copper mining and processing firms for the period covered 1956-1981 was used. The restricted profit function which has a generalized Leontief-quadratic functional form was presented in econometric form and estimated using Panel Instrumental Variables procedures to obtain the parameter estimates. Following Wald tests, he found that the managers in nine copper extracting firms are behaving in a manner consistent with a vertically integrated of a price taking nonrenewable resource firms. The Bayesian inequality constrained estimator was employed as a robustness check. The study outlined that, in percentage terms, the Bayesian estimates of the restricted profit function which satisfies refutable implications of the Hotelling theory are not much different with estimated restricted profit functions estimated by instrumental variables technique. Despite difficulties arising due to limited data for theory testing, the Hotelling's theory is supported empirically by a probability value of 0.82.

Leinert (2012) conducted an empirical test of Hotelling's hypothesis of increasing resource price to investigate whether the crude oil price adjusts to unexpected news about the oil field discoveries. She tested the static and dynamic Hotelling's conditions for 20 unanticipated crude oil field discoveries from giant oil fields discovered after 1990 and

investigated their effect on the oil market. She applied the event study methodology to identify the degree of discovery and compare with daily return of discovery events with some return benchmark. The regression model was estimated with Generalized Least Square (GLS) Prais- Winsten procedure. The results found the price of crude oil declines by 0.88% on average during the discovery period. Thus, there is evidence of price adjustment as a result of unanticipated increases in resource availability during the discovery period. Similarly, she found that the price adjustment as a result of new discoveries is closer to the predicted and expected social optimum value according to Hotelling's model. The study concluded that, Shadow price is essentially a key component that explains the power of Hotelling's rule, is important in the evolution of resource prices and it can bring significant distinction between nonrenewable and renewable resources on price formations.

Soren *et al* (2014) studied the extended Hotelling's model and recast it to be a drilling problem rather than a production problem. The study explained why producing at the flow constraint could be optimal even when the prices are expected to increase faster than the interest rate. The time series crude oil drilling and production data were used for Texas Rail Road Commission (TRRC), New York Mercantile Exchange (NYMEX), West Texas Intermediate (WTI) for the period 1990-2007, and rig rental data for the period 1990-2013. The Generalized Least Square (GLS) procedure was employed with lagged difference to minimize Akaike Information Criterion (AIC) to empirically estimate the oil production, spot and future prices. They found that oil production declines asymptotically toward zero and production was not affected by shocks pertaining to spot or expected future prices, while drilling of a new well and rental prices of drilling rigs respond strongly to oil price

shocks. They contend that the reasons for the decline in oil production are due to loss of underground reservoir pressure that results from cumulative depletion and cost structure of the oil industry. Furthermore, decisions to extract the oil is solely made depending on well-by-well, and not barrel-by-barrel, because the resource flow is constrained by individual reservoir pressure and the costs of investment for new well. They concluded that, the extended Hotelling-style model that is based on the actual cost structure of the oil industry can provide predictions which are empirically valid. Hence, the results they obtained can renew the interest to employ the Hotelling model to predict the behavior and understand markets of natural resource in the future.

Divovich (2011) undertook an empirical test of the Hotelling model for the rare earth market using data from 1955-2009. Globally, due to rapid growth in technology, rare earth resources are in dramatic high demand to make different digital devices like rechargeable batteries, cell phones, laptops, medical devices and computer memory. Divovich used what he called best-case marginal cost function which was in the form of polynomial to obtain the estimated time path of marginal cost and compared with historical data for the available data. Assuming the rare earth follows perfect competitive industry, two tests were performed with a variety of functional forms such as quadratic time argument together with best case marginal cost before carrying the regression. The models for two tests were estimated using OLS that yielded the appropriate and most significant coefficients for the time path of marginal cost. Both tests were found to predict a U-shaped marginal cost functions which seemed to be consistent with current theoretical and empirical literature. Despite being unable to formally reject or accept the Hotelling rule due to lack of cost data,

the rule was not consistent with data when a structural shift for increased environmental costs was allowed.

Rare earth minerals are considered rare minerals in the earth because of scarcity on their concentration, economically exploitable reserves, high technology, significant capital, costly investment, high level expertise needed and the remarkable impacts on the extraction and surrounding areas. These minerals took almost ten days extraction process at the initial stage before going to other processing steps. Among them includes bastnäsite, monazite, loparite, cerium, yttrium, lanthanum and neodymium.

Neumann and Erlei (2014) conducted an empirical investigation of Hotelling's model and price formation of nonrenewable resources using methods related to experimental economics. Their experimental design consisted of a computerized continuous double auction (CDA) of an exhaustible resource that lasts for 10 periods. Since the experiment had a short time horizon, they chose the interest rate of 20% in order to generate a dynamic equilibrium path with substantive prices and quantities. Using least square regression model, the study found the price of \$ 3.82 for all markets. Price formation of the aggregated 10 markets was monotonically increasing in series as predicted by exponential growth law. Moreover, the experiment found a convex shape price path for nonrenewable resources. They concluded that, Hotelling rule is still relevant for the long-term settings and development of natural resource prices. Lastly, the study suggests future research need to test the Hotelling model with other experimental designs and techniques which accounts for changes in time preferences, interest rates as well as the inclusion of backstop prices and technologies in their estimated models.

## **2.3 Optimization Process and Excel Spreadsheet Solver tool**

This section provides the theoretical review of linear programming and numerical analysis, which involves simulation and optimization. We also present the empirical literature regarding optimization process using excel solver for different natural resource extraction. Dynamic optimization and extraction paths can be conducted using different optimization tools and software such as General Algebraic Modeling System (GAMS) Solver and Excel Spreadsheet Solver. An Excel Spreadsheet Solver from Microsoft software can be applied in different sections of natural gas value chain. It can be used for optimizing resource extraction, processing and production, pipeline transportation as well as marketing. An Excel spreadsheet Solver tool helps in understanding the dependence of various optimized variables when performing inter-temporal analysis and time preference on natural resource extraction. Always, a Solver uses an algorithm that needs to have an initial estimate of the optimal time path of a resource (Dastjerdi *et al*, 2009).

### **2.3.1 Empirical literature on Optimization Process**

The selection of the objective function and designed parameters to optimize can be altered to achieve the best solution using Microsoft Excel Spreadsheet Solver to achieve the desired goal. The objective can either be maximizing the sum of discounted profit, discounted cash flows or minimizing resource extraction or minimizing oil and gas pipeline transport costs.

In his study, Huck (2005) solved a three player differential game between agents and conducted optimization process for exhaustible resources. He used an excel spreadsheet solver as a tool to describe and estimate a Nash equilibrium of simple differential game. The model specified is that a player maximizes its profit, taking into consideration the

extraction paths of other competitors when it is optimizing its own extraction path as in an open-loop Nash equilibrium. The players differ in initial resource stocks, extraction costs and discount rate among others. He chooses the time horizon of 100 periods for uniform distribution of initial stocks. He simulated the optimized model of discounted profits based on Excel Solver and obtained the depletion paths. The results shows that the exhaustible resources are used up totally in 95 periods. Therefore, the optimized algorithm model described the existence of Nash equilibrium model in the interaction of three player games when accounting for resource management and sustainability.

Dastjerdi *et al* (2009) ascertained the role of time preference in inter-temporal allocation and determining the extraction levels of the ore mineral. They used annual experimental data for ore extraction to describe the effects of time preference on nonrenewable resource management. The value of mine in the form of discounted cash flow over time was set up as a dynamic optimization problem with discount rate of 0.08 and 0.02 respectively. Excel Spreadsheet solver was used to simulate the extraction path for ore. Using 0.08 rates, the optimal time path of ore extracted was 580.69 tons in the first year and reduced to 395.2 tons in the following year. These values presented the downward sloping optimal path because the discount factor induces speedy ore extraction. They also found that the discounted value of mine was 504.06 when the discount rate is 0.02. At 0.02 discount rate, there is also an incentive for mine owner to extract ore quickly and it has shown the optimal path of extraction is steeper than when the discount rate was 0.08, because future cash flows were discounted more. The study found that higher extraction rates of ore will occur if time preference is also higher. They concluded that, the higher rate of time

preference which follows from higher discounting factor induces more and fast extraction of ore.

Sund (2010) developed a framework that dealt with a decentralized optimization problem with self-interested agents. He also aimed at optimizing the resource allocation among principal and agent relationship in a drilling project of oil and natural gas resources. He analyzed how the principal - agent relationship could lead to opportunistic behavior on resource allocation, resource flow from agents and transaction costs of drilling projects. The study used two constraints such as incentive compatibility and participation constraint to obtain the objective function of optimizing the resource bundle value. Sund optimized the resource allocation by using Excel Solver tool. He found that the “democratic” resource allocations would ultimately lead to higher profits for all agents and principals involved in the business.

## **2.4 Conclusion**

The above literature review demonstrates that most of the studies modify Hotelling’s basic theoretical framework to allow for more realistic features in the model such as changes in extraction costs, prices, risks, changes in the stock of reserves and technological progress. Researchers argue that empirical outcomes are likely to differ from one country to another because of the difference in the types and forms of resources they own and nature of operating markets. Also, outcomes differ time to time, even when same modelling techniques are employed. Most of the existing empirical studies done so far aimed at testing the Hotelling’s framework and describing optimal extraction paths of the nonrenewable resources data in developed nations and little have been conducted in SSA. Thus, this study aims at filling the gap by looking at how decisions are taken by firms

towards the optimal extraction of nonrenewable resources specifically natural gas industry in Tanzania, and if at all firm's extraction paths conforms to Hotelling's dynamic condition. Hotelling's test is important for gas sector in Tanzania because it helps to know the extraction path, factors affecting cost of extraction and the stock of remaining reserves that will influence the future pattern of extraction.

Moreover, understanding the optimal extraction path is significant in planning and adjusting current and future society's benefit, government design of its policies like setting the market price for the resource. Additionally, it is necessary for the firm's to design and set up strategies regarding levels of extractions, profit and cost structures. Hotelling's rule is also significant in maximizing present and future asset value of natural gas firms as well as country's natural gas sustainability.

## **CHAPTER THREE**

### **OVERVIEW OF THE NATURAL GAS SECTOR IN TANZANIA**

#### **3.0 Introduction**

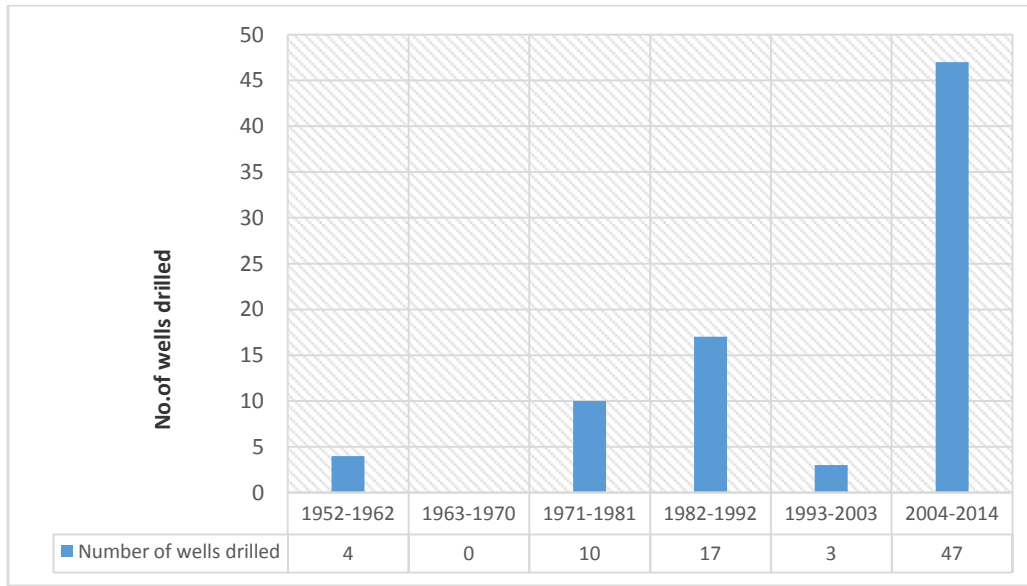
This chapter provides an overview of the Natural gas Sub-sector in Tanzania and it's organized into eight sections. Section 3.1 provides a short history of the natural gas sub-sector in Tanzania, Section 3.2 discusses Natural gas Upstream, Midstream and Downstream activities. Section 3.3 explains the key institutional and policy frameworks. The main frameworks discussed include the Natural Gas Policy 2013, Petroleum (Exploration and Production) Act of 1980, the Petroleum Act of 2008 and the Extractive Industries Transparency Initiatives (EITI). Section 3.4 shows the existing oil and natural gas fiscal regime in the country. Section 3.5 provides the contribution of natural gas Sub-sector to GDP, growth and development in Tanzania. And the last section presents a natural gas production and consumption in the country.

#### **3.1 Natural gas sub-sector in Tanzania**

Tanzania has a large natural gas reserves along the Eastern coast of Africa. Currently, the extractive industry is one of the fastest growing industries in the country, (Shanqhvi and Jingu, 2013). Natural gas exploration and discoveries started in 1970. Initial discoveries of natural gas occurred on the Songo Songo island in 1974, but the surveys and the exploration process stagnated due to the non-readiness of the country to develop the sector, limited technology as well as lack of capital. Exploration was re-activated around 2000's and more discoveries were made from 2007 to 2013. Currently, Tanzania has about 50.5 trillion cubic feet (tfc) of proven reserves of which 94% are offshore and 6% onshore. Offshore natural gas reserves of about 42.5 tfc will be directed at Liquefied Natural Gas

(LNG) production and onshore reserves of around 8 tfc will be directed at power generation facilities in the country. Recently, more multinational companies and investors are looking for the opportunities to invest in natural gas sector and other related activities. There are about 17 natural gas companies doing seismic surveys and exploration. Currently, about 47 wells have already been drilled since commencement of natural gas production for commercial purposes in 2004. More exploration and discoveries are being made both onshore and deep water.

The government has signed a contract with a Chinese contractor to build a 36” pipeline from Mnazi Bay, Mtwara region to Dar es Salaam and a 24” branch from Songo Songo to Somanga Fungu to tie in to the 36” pipeline. The project has been funded on loan basis of approximately USD 1.2 billion from Exim Bank of China. Also, two natural gas processing plants in Mnazi bay and Songo Songo fields will be constructed with the capacity of 210 and 140 Million Metric Standard Cubic feet per day (mmscf/day) of natural gas respectively (Shanghvi and Jingu, 2013). The new pipeline of 36” inches will have the carrying capacity of 784 million cubic feet of natural gas per day. The pipeline will be able to transport and distribute the amount of natural gas according to demand for the next 20 years (TPDC, 2012). The transported gas is expected to be used for domestic household consumption, source of heat in industries and the country’s power generation.



**Figure 3.1 Natural gas wells drilled in the period of 1952-2014**

*Source: TPDC (2014a)*

Figure 3.1 shows the number of exploratory, dry wells and discovered wells drilled up to July 2014. Before Independence, only four wells were drilled, and from 1971-1981 about 10 wells drilled but there was no development after drilling. From 1982-1992, more wells were drilled despite the technology being limited. The government established various projects together with multinational companies and national oil company to develop the natural gas industry.

From 2004-2014, more wells were drilled by foreign firms who came to invest in natural gas industry from 2007 to 2013. Out of 47 wells drilled from 2004-2014, 28 wells have confirmed to have natural gas reserves and others are just exploratory or dry wells.

### **3.2 Natural Gas Upstream, midstream and downstream Activities**

Oil and gas operations are usually categorized into three major stages which are upstream, mid-stream and down-stream operations.

### **3.2.1 Upstream Natural Gas operations**

Upstream operations involve seismic surveys, exploration, discoveries, extraction and production of oil and natural gas from both onshore and offshore fields. Onshore field areas are the ones found on the mainland and near water bodies and the natural gas is extracted by drilling the rocks downward. Offshore areas are oil and natural gas fields found in deep waters and gas is extracted on the water-bed or seabed rocks. Onshore areas include shelf up to water depths of 500 meters, while offshore areas include water depths beyond 500 meters. In upstream areas, the oil and gas companies can develop and drill the wells either for exploratory or for the production of natural gas. Therefore, upstream activities involve extraction from wells and processing of oil or natural gas reserves. Figure 3.2 shows the map of Tanzania displaying various licensing blocks that are currently under development and discovery stages. There are about 12 blocks found in the offshore areas (deep sea).

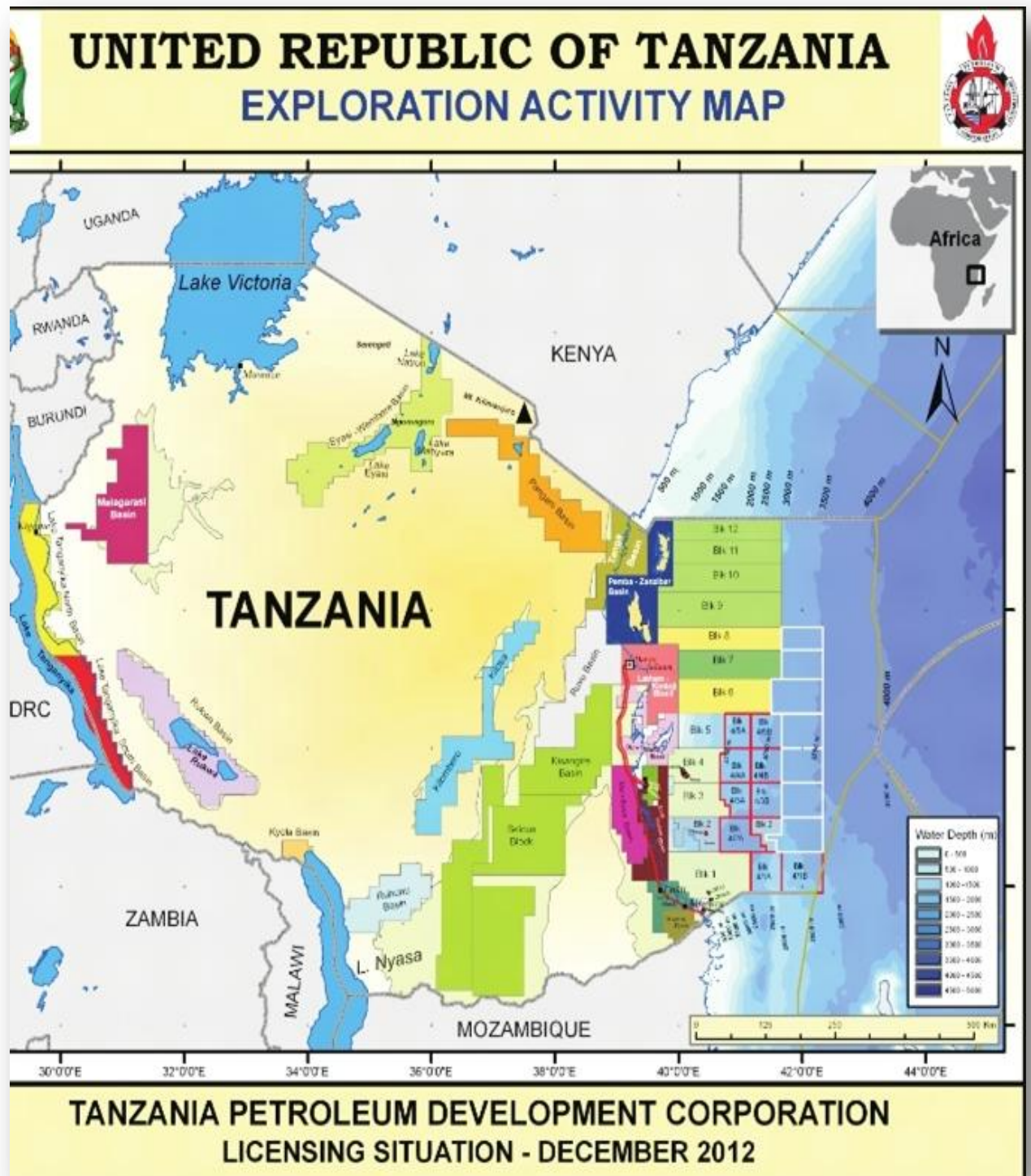


Figure 3.21 Natural gas discovery blocks in Tanzania

Source: TPDC (2014a)

### **3.2.2 Midstream Natural gas operations**

Mid-stream includes such activities like natural gas processing plants, refineries, retail outlets and distributors, storing and transporting through oil and gas tankers or natural gas pipeline networks. The pipeline is the common way used to transport and connect vast networks of natural gas to long distances. Currently, Tanzania has a 16” inch transmission pipeline, which transports natural gas to power plants to generate electricity and for various industrial uses.

### **3.2.3 Downstream Natural gas operations**

Downstream activities provide a crucial link between gas producing areas and the final users of finished products which includes individuals and companies. Downstream operations connect the demand section, consumers and industry. This section propels growth of the country and helps to expand consumption and production activities including the service activities of marketing, insurance and banking services.

About four companies are carrying downstream natural gas activities which are Tanzania Development Corporation, Pan African Energy Tanzania Limited-Orca Exploratory Group operates and Maurel & Prom. The Orca Exploratory group also operates a gas processing facility at Songo Songo Island on behalf of Songas Limited (Songas). The processing plant supplies natural gas for the power sector and industrial markets. Natural gas is transported to a 25 km 12” offshore pipeline and a 207 km 16” onshore pipeline.

### **3.3 Institutions and Policy**

The Tanzania Ministry of Energy and Minerals (MEM) is a policy and lawmaker for the petroleum and natural gas sub-sector in Tanzania. It also regulates the petroleum upstream activities and grant petroleum exploration licenses to the Tanzania Petroleum Development

Corporation (TPDC) institution on behalf of the government. Afterwards, TPDC enters into production sharing agreements with multinational companies on behalf of the government.

### **3.3.1 Natural Gas Policy (2013)**

In 2013, the first draft of natural gas policy was adopted to address various issues pertaining to the industry.

Specifically, Natural Gas Policy (2013) in Tanzania was formulated to:

- Develop a competitive and efficient domestic and export market for natural gas, and ensure that the government and Tanzanians participate effectively in the natural gas business.
- Make available trusted and transparent mechanism for management of natural gas revenues.
- Develop a natural gas infrastructure and ensure compliance with health, safety, security and environmental standards in the natural gas value chain.
- Create an environment that will attract foreign and local investment into the gas industry.
- Build an effective institutional and legal framework to administer the industry
- Promote linkages between the natural gas industry and other strategic sectors in the economy.
- Institute appropriate pricing structure to sustain supply and demand of natural gas.
- Ensure reliability of natural gas supply
- Ensure benefits are obtained from the natural gas industry through PPP projects.
- To manage public expectations on benefits coming from the natural gas industry.

The main aim of the Natural Gas Policy, 2013, is to provide guidance for the sustainable development, utilization of the resource and maximization of the benefits, so that the natural gas industry will contribute to the transformation and diversification of Tanzanian economy.

The Natural gas policy formulation was aligned with the National Energy Policy 2003, the Five Year Development Plan (FYDP), 2011/12-2015/16, the second National Strategy for Growth and Reduction of Poverty (NSGRP) 2010/2011-2014/15, National Development Vision 2025 and other cross-sectoral policies. NSGRP emphasize on leveraging returns on natural resources like natural gas. They explain that natural gas as energy resource has significant potential to foster growth, poverty reduction and provide regional development.

The study found that the natural gas policy has explicitly described how the country is set up to become an emerging energy producer, by envisaging the establishment of various mechanisms and institutional frameworks to foster the growth of the sector and achieve its set objectives. The policy acknowledges the need for appropriate legal and regulatory framework, flexible pricing mechanism, management of revenue and the role of local content and capacity building for the growth and development of the energy sector. It has emphasized the role of the sub-sector in promoting the establishment of various industries, power generation, domestic consumption before export, as well as linkages to other sectors and its contribution to the economy. The policy has also put forward frameworks and institutional capacities that will ensure monitoring and evaluation of the sector to achieve long term benefits. These include natural gas utilization master plan, natural gas Revenue fund, natural gas act and regulation, the national gas company and its subsidiary companies. The role of private sector participation is also highlighted as crucial in

promoting investments, technology, manpower and linkage from upstream to downstream operations.

One setback of the policy is that it does not explicitly explain the role of institutions in ensuring external competitiveness in regional trading and international markets. The objectives are not clear on how to promote sound development of international gas markets and regional benchmark prices along the eastern coast especially for Liquefied Natural Gas (LNG) business. It must be noted that commercial competitiveness and vibrant market across the border have an effect on the exports, pricing structure as well as short and long term gains generated in the country. Also another setback is that, the policy framework of establishing various institutions which might have similar and competing roles may lead to resource inefficiency in the future. For example, the policy envisages the establishment of natural gas revenue fund, National Oil and Gas Company and its subsidiary companies while the existing institution (TPDC) acts on behalf of the government on matters related to oil and natural gas development in the country. All these institutions are being set to cater for management, monitoring and evaluation of oil and gas resource in the country. Establishment of multiple institutions may render to competing and conflicting roles in future.

### **3.3.2 Petroleum (Exploration and Production) Act (1980)**

The Petroleum Act (1980) is one of the key instruments governing the upstream oil and gas activities, operations and development in the country. It is an act of Parliament stipulating various items that are incorporated under a law to indicate the ownership, exploration, licensing and production operations of all petroleum products in Tanzania. The law requires Exploration licenses (EL) to be given for a period of eleven years. If there is a

successful discovery after seismic surveys and exploration, then a company is given Development license for 25 years plus additional 20 years for discovering the area.

The Act also provides a framework for: Administration of the Petroleum upstream operations; Issue, Renewal and Cancellation of licenses; Surface Rights; Disputes Resolutions; Financial Provisions; Miscellaneous and Regulations. The Petroleum Act (1980) is designed to facilitate a favorable legal environment for the extractive companies (MEM, 2008).

### **3.3.3 Other legal frameworks**

#### **3.3.3.1 Petroleum Act of (2008)**

This is the legislation governing oil and gas midstream and downstream operations. The Act is applicable to Tanzania mainland only and it is not related to exploration, development and production of oil and natural gas products. The Act specifies issues on: administration and regulations; petroleum operating licenses; approval of works for the construction of petroleum operations; the obligation of the holder of an approval or licenses; assurance of fair competition; public health, safety and protection of the environment, petroleum product prices; petroleum supply operations; offenses and penalties; and Disputes Settlements and Miscellaneous Provisions. It also applies to the handling and provision of petroleum products, transportation, storage and market.

According to the Petroleum Act of 2008, Energy, Water Utilities Regulatory Agency (EWURA) use sector legislation and the EWURA Act. (CAP 414) to regulate the natural gas midstream and downstream operations in Tanzania. EWURA has the mandate to perform economic, technical and safety regulation functions concerning natural gas sub-

sector in the country. EWURA also offers construction approvals for petroleum installation and operating licenses to oil and natural gas marketing companies (MEM, 2009).

### **3.3.3.1 Extractive Industries Transparency Initiative (EITI).**

EITI is a global standards institution for governance of the natural resources that require governments to engage citizens in the matters pertaining to the extractive industries in the country. In 2009, Tanzania decided to join the Extractive Industries Transparency Initiative (EITI) in the efforts to promote transparency in the extraction of minerals like Gold, diamond and Tanzanite as well as oil and natural gas. Tanzania implemented EITI by establishing a Tanzania Extractive Industries Transparency Initiatives- Multi- Stakeholders Working Group (TEITI-MSG) to promote transparency and accountability in Tanzania's Extractive Industries. The group is made up of civil society organizations, extractive companies and the Government. Tanzania Extractive Industries Transparency Initiatives (TEITI) are working on a compliance work plan which aims at strengthening and deepening transparency in the extractive industries, so that the public understand the accountability of the revenues generated by the sector and how they will be used. As of 2014, Tanzania had already prepared four EITI reconciliation reports. EITI reconciliation reports are prepared by an independent firm annually. The reconciliation report provides information on the payments made by extractive companies and revenues obtained by the government. On December 2012, Tanzania was declared compliant with EITI rules and Standards as the country has demonstrated an effective process of disclosure and reconciliation of revenues from its oil, natural gas and mining sectors (URT, 2014).

### **3.4 Oil and Natural gas Fiscal regime in Tanzania**

The main contractual arrangements that are made between natural gas companies and the government in various countries includes Concession Agreements, Service Agreements and Production Sharing Agreements (PSA's). Tanzania has adopted production sharing agreements as a model of fiscal regime that will ensure the government participate fully in the operations of the oil and gas industry, obtain revenue and ensure that international investors recover their costs and profits. The government's key fiscal objectives are early dependable income, limited exposure to risk, a significant share of resource rents that will ensure profitability, minimize opportunities for tax evasion and lastly, the broad based sector development (Killagane, 2012).

The fiscal regime and terms that are used for the oil and natural gas upstream activities in Tanzania are basically based on Petroleum Act 1980, the Income Act No.11 of 2004 and a model of production sharing agreement entered between a company and TPDC.

#### **3.4.1 Production Sharing Agreements (PSA's)**

The Production Sharing Agreement (PSA's), is the negotiating instrument with natural gas companies that are interested in investing in the natural gas sub-sector in Tanzania. The model offers the baseline information for fiscal regime and nature of contract on the terms to be negotiated with the government, which are later concluded in the Production Sharing Agreement (PSA). PSA is a tripartite agreement and the parties includes; the Government of the United Republic of Tanzania through the Ministry of Energy and Minerals, Tanzania Petroleum Development Corporation and the natural gas exploration company (URT, 2013). PSA provides an opportunity for cost recovery if there is successful exploration and discovery of petroleum products for International Oil and natural gas companies.

Key components of Tanzania's PSA include; royalty payments, taxation and cost recovery. Others are oil or gas profit, government participation, domestic market obligation and bonus payments (TPDC, 2008). Below are the two key components of revenue:

**Royalty:** under section 81 of the Petroleum Act, a registered holder of a development license must pay a royalty rate of 12.5 percent for onshore areas and 7.5 percent for offshore areas. It includes royalty payment of total crude oil or natural gas production before any cost recovery to the government, in respect of the petroleum product obtained from the development area.

**Taxation:** the company is subject to income tax under the Income Tax Act at the standard corporate income tax of 30 percent. Under the Model of Production Sharing Agreement, the company is obliged to pay an additional Profit Tax calculated on positive net cash flow on a development area of onshore or offshore fields. The Income Tax Act also specified for a 20 percent depreciation rate for assets used in natural resource activities.

Tanzania has already signed 26 PSAs for onshore and offshore gas exploration blocks as of June 2014. PSA's shows the share of profit for companies and government revenue after gas extraction (see table 3.1 and 3.2 below). Currently, there are three versions of PSA's that exists. The first PSA was made on 2004 and second on 2008. In September 2012, the Energy Minister announced a review of 2008 PSA's and made the third PSA in 2013 to ensure the country's best interests are obtained.

**Table 3.1 Profit sharing between TPDC and gas investor for onshore and shelf blocks**

Daily total production rates (mmscf/day)	Share of profit	
	TPDC (%)	Contractor (%)
0- 19.99	60	40
20-39.99	65	35
40-59.99	70	30
60-79.99	75	25
80 and above	80	20

Source: TPDC (2013)

**Table 3.2 Profit sharing between TPDC and gas investors for Deep water blocks and Lake Tanganyika North**

Daily total production (mmscf/day)	Share of profit	
	TPDC (%)	Contractor (%)
0- 149.999	60	40
150-299.999	65	35
300-449.999	70	30
450- 599.999	75	25
600- 749.999	80	20

Source: TPDC (2013)

### **3.5 Contribution of the Natural gas sub-sector to the Tanzanian economy**

Energy plays a crucial role in the existence of every economy (Dunkerly et al, 1981). Energy resources are critical to the growth of Tanzanian economy. Tanzania natural gas extraction has brought significant contribution to the growth of its economy through increased production, enhanced domestic market performances and increased investments. The natural gas sub-sector is anticipated to play a vital role in the areas of power generation, growth of industries, employment opportunities, FDI inflows, government revenue as well as socio-economic development of the country (TPDC, 2013).

### **3.5.1 Power generation**

Natural gas as energy resource has become an area of concern regarding its significant benefit of being convenient, environmentally friendly and cheap source of input for industries and power generation. Power generation using natural gas is environmentally friendly with low carbon dioxide emissions. With the country's increasing demand for power and unpredictable pattern of rainfall to generate hydro-power since 2009, natural gas has become the key energy resource. Compared to other energy source such as a liquid fuel, thermal, hydro and biomass that are used to generate power in the country, natural gas production ranks the highest reliable energy resource with a total of 46.4% grid and off-grid production in 2012 (USEA, 2013). Also, about 37 different industries in Dar es Salaam city are served with 100% natural gas supply. Among them are Cement, plastic, iron melting, textile and aluminium industries.

### **3.5.2 Establishment of Industrial base**

Various industries such as Natural gas processing plant at Songo Songo, Cement Industry, Fertilizer industry, Ammonia and Urea fertilizer processing plants, Methanol processing plant and Liquefied Natural gas (LNG) plant are expected to be established as a result of natural gas usage. Natural gas is known to be a cheap raw material and input of fertilizer and methanol processing industries. Moreover, the industries are expected to use natural gas as a source of heat and power. Therefore, cheap availability of natural gas is expected to promote investment of the industrial park, increase productivity, accelerate trade, employments and foster growth in the country.

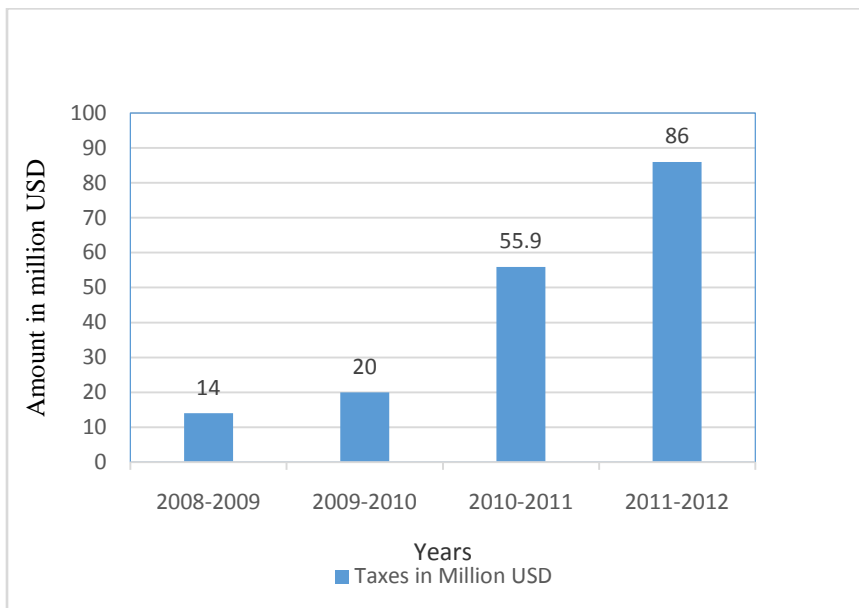
### **3.5.3 Employment Opportunities**

The natural gas sub-sector is capital intensive in nature and requires a limited number of labour supply like other sectors under the extractive sectors in the economy. However, following natural gas development and established industries, it is expected that more than 3000 formal and 6000 informal employment opportunities will be created (TPDC, 2013). More manpower is needed to establish infrastructure, work on processing plants, production sites and industries. Capacity building to ensure maximum Tanzanian local content participation in the gas sector is of crucial importance. The Tanzania natural gas policy sets objectives to empower local people to effectively participate in the natural gas value chain and resource development. Thus, citizens are encouraged to acquire prerequisite skills and knowledge in various institutions to promote the local supply of labour and reduce the reliance on foreign expertise. Also, exploration and production companies offer skills and required training on subject matter as part of company's social corporate responsibility to empower Tanzanians to serve in the natural gas sub-sector.

### **3.5.4 Revenue collection through taxes**

The revenue from natural gas and related activities are expected to bridge the government budget gap and stimulate economic growth. Foreign Direct Investments brought significant contribution to the economy as a result of foreign currency inflows. In addition, Construction of industries, gas powered plants and expected LNG business and trading are further expected to increase productivity and bring revenue to the government. Similarly, revenue fund is going to be established for investing the proportion of revenue obtained to cater for intergenerational issues and concerns. The Extractive Industries Transparency Initiative (EITI) report (2013), shows that revenue to the government from natural gas

extraction has steadily increased over time as reported and reconciled by both companies and the government entities. Recently, the inflow of international oil and gas companies to invest in the gas industry and related activities in the country, contributed to the rise of government revenue through different forms of taxes. Figure 3.3 shows that the revenue collection of different taxes charged to natural gas exploration and production companies grew from 14 million USD to 86 million USD between 2008 and 2012.



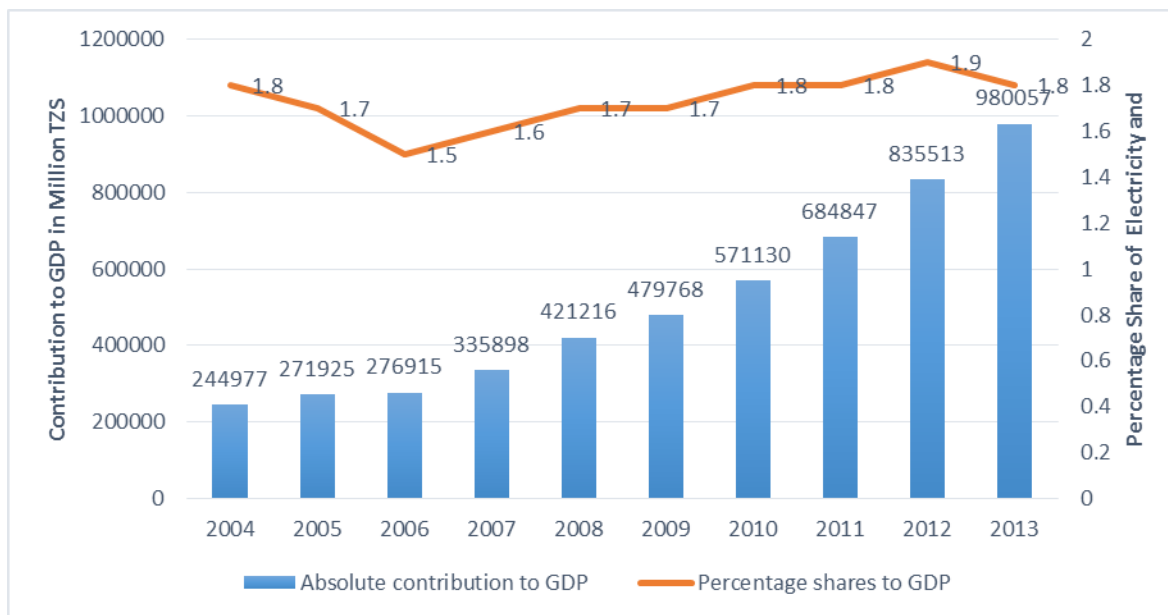
**Figure3.2 Revenue generated from natural gas resource through taxes (\$ USD Millions)**

Source: Extractive Industries Transparency Initiative - EITI report (2013).

### **3.5.5 Contribution of Electricity and Natural Gas sub-sector to GDP**

The share of electricity and gas activity to GDP had remained slightly lower compared to other economic activities like mining and quarrying and manufacturing activities under Industries and construction sub-sectors. Figure 3.4 indicates that electricity and natural gas sub-sector grew steadily from 2007 to 2012 both in absolute terms and as a share of GDP

at current market price. A significant share of 1.8 percent of GDP was recorded when natural gas production on commercial basis started in 2004. From 2005 to 2011, the contribution of electricity and natural gas as a share to GDP has remained almost constant at 1.7 percent per year. In 2012, this figure increased slightly to 1.9 percent compared to 1.8 percent in 2011 but fell again to 1.8 percent in 2013.



**Figure 3.3 Share of electricity and Natural Gas to GDP at current market price**

Source: Tanzania National Bureau of Statistics-NBS (2013)

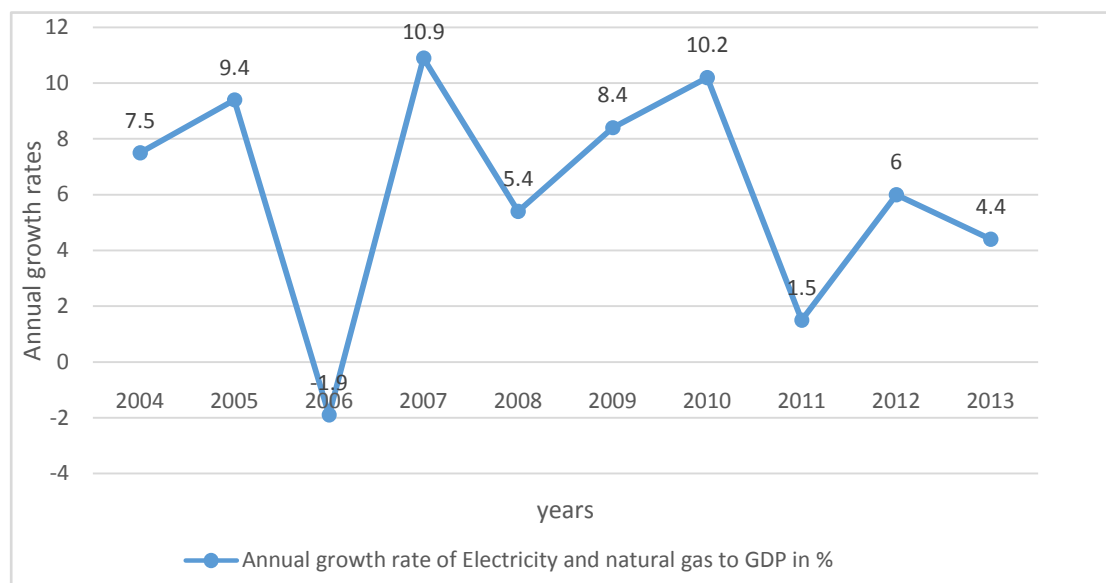
Although the percentage shares of electricity and gas activity to GDP at current market price was slightly fluctuating, its contribution in absolute terms significantly rose from 2004 to 2013 as indicated in figure 3.4. An approximate amount of 250,000 million Tanzanian Shillings (TZS) was obtained in 2004, but the figure steadily grew to amount of 980,000 million TZS in 2013. The natural gas sub-sector is expected to be the fastest growing sector in Tanzania's economy in the next decade. The impact of the gas sub-sector to the economy has far been integrated for both forward and backward linkages.

Currently, the forward linkages include electricity and power generation to industries and national grids. The sector is also expected to provide outputs that will be used as intermediate inputs by other established industries. The industries that will benefit in the country includes cement factories, fertilizer and petrochemical industries. Also, the indirect benefits to the gas sector from other sectors of the economy are in-terms of fuel, power, sub-contracting services like expatriates and other material inputs like renting drilling rigs and chemicals supplied by local producers to gas related activities. This is termed as backward linkages of the sector.

### **3.5.6 Growth of the Natural gas sector**

Annual growth rates of the electricity and natural gas sub-sector has not been smooth over the period 2004 to 2013. Figure 3.5 shows that, electricity and gas activities growth rate have remained low with the exception of 2007 and 2010 where the growth rate recorded was about 10.9 and 10.2 percent higher compared to other years. In 2006, the electricity and gas sub-sector recorded a negative annual growth rate of about 1.9 percent and sharply rose to 10.9 percent in the following year 2007. From 2011 to 2013, the sector experienced a decreasing annual growth rate of 1.5 percent to 4.4 percent, despite its significant growth in absolute terms. The reasons for the rise and fall in the annual growth rate of the sub-sector might be attributed to risks and difficulties associated with solving the energy crisis in the country and increased fiscal arrears that hamper the growth prospects of the whole energy sector. Global financial crisis also influenced the decline in the annual growth rate of the sub-sector between 2008 and 2009 where growth rates of 5.4 percent to 8.4 percent were recorded. The crisis led to limited foreign inflows and low capital financing in the country. Even though the growth rate of the sector has not been remarkable lately, it is

expected that the new gas discoveries, inflows of FDI and additional fiscal revenues will stimulate growth of the natural gas sub-sector in near future.



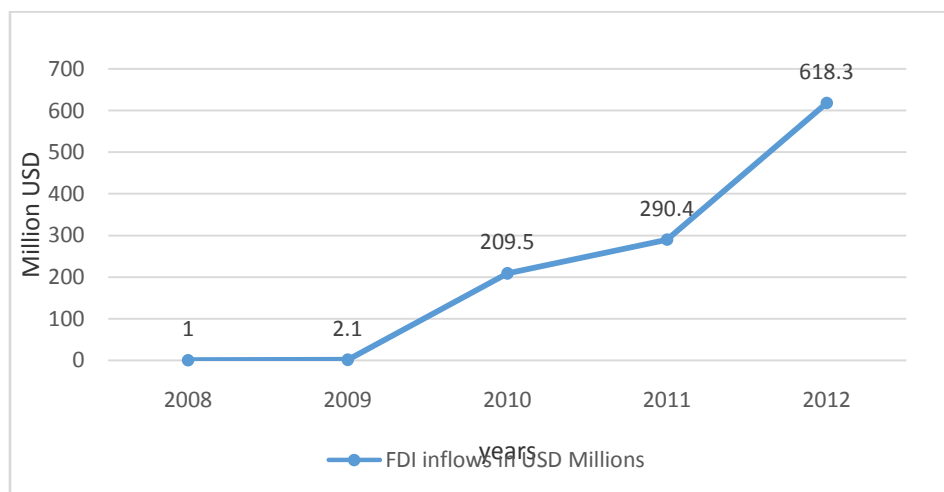
**Figure 3.4 Growth rate of the electricity and Natural gas sector (%)**

Source: Tanzania National Bureau of Statistics (2013).

### 3.5.7 Foreign Direct Investments (FDI) Inflows

Developing countries having abundant natural resources or large market size tend to promote and attract more foreign direct investment (FDI) in their countries (Asiedu, (2006): (2013). Tanzania has promoted more FDI inflows in natural gas resource sector in recent years. In 2012, the country experienced a sharp increase in inflows to electricity and natural gas sub-sector. Figure 3.6 indicates that the sector recorded approximately 618.3 Million USD in 2012 which was higher compared to 2011 and 2010 where the sector recorded 209.5 and 290.4 Million USD respectively. The natural gas sub-sector had lower direct investment during 2008 and 2009, where only 1 and 2.1 million USD were obtained. The inflows are coming from the United Kingdom (UK), United States and Canada. Favorable institutional policies and strategies set in the country led to the attraction of

more inflows and investments that influenced growth and economic development. Compared to other sectors of the economy, mining and quarrying and electricity and gas activities continued to rank highest in attracting FDI inflows in Tanzania over the period of 2011 to 2012. FDI inflows in the country were financed through equity and investment fund shares to Greenfield investments, particularly electricity and natural gas Sub-sector in 2012. Furthermore, companies that made new discoveries in offshore Tanzania, such as Statoil and British Group (BG) plan to build LNG terminal worth about 10 billion USD. This is expected to be a relatively huge investment and a significant FDI inflow for a country like Tanzania.



**Figure 3.5 Foreign Direct Investment inflows to natural gas activities in Tanzania**

Source: Tanzania National Bureau of Statistics (2013).

### **3.6 Natural gas production and consumption**

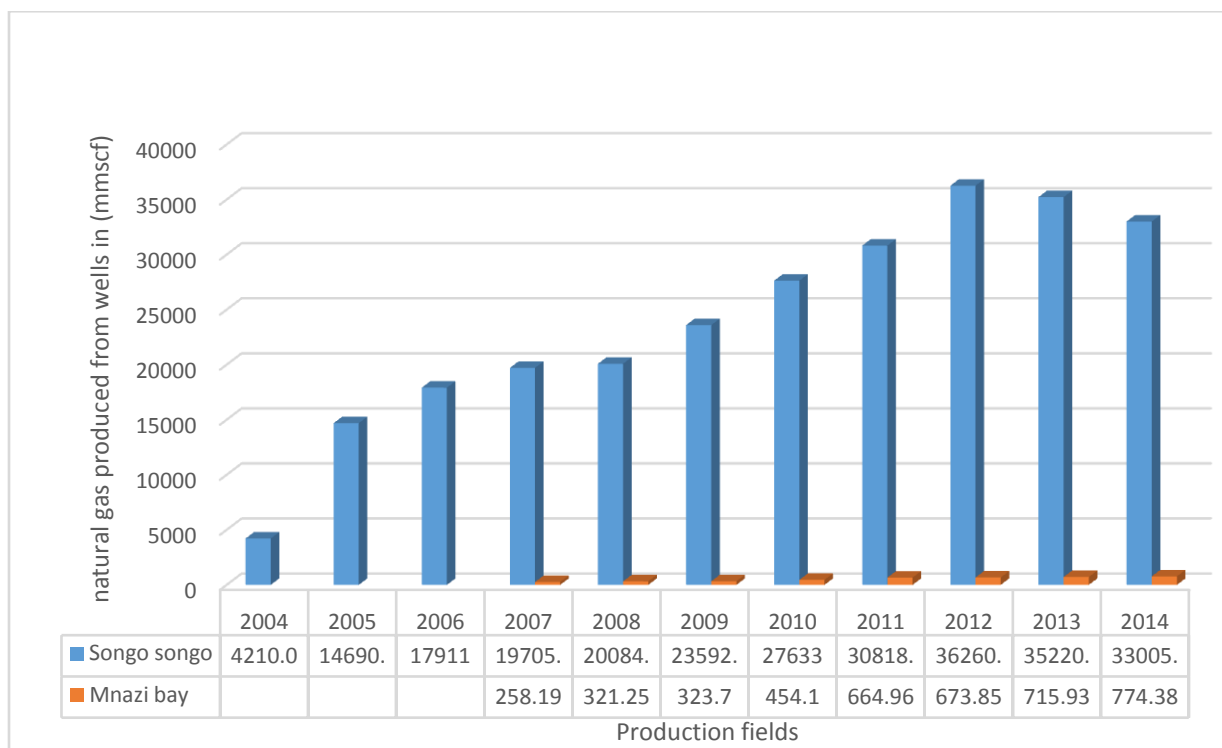
Natural gas investments in a country take longer time between planning, gathering seismic data up to production. Therefore, to develop natural gas resource, for commercial production needs time to set up necessary infrastructure. Typically, it takes at least eleven years to initiate natural gas investments and development activities. In Tanzania, the initial

exploration period is four years, which can be extended twice, first for another four years, and then for three more years with TPDC approval if the company will give any justification for delay (TPDC, 2013).

Since 2011, Songo Songo and Mnazi bay fields have been the key producers of natural gas in Tanzania despite emerging companies which are still in the exploration and discovery stages. Currently, the produced natural gas is used only for domestic consumption. It is estimated that, by 2020, the country will be a significant exporter of Liquefied Natural Gas (LNG) (URT, 2014).

### **3.6.1 Natural gas production**

Till December 2011, Songo Songo consisted of about 5 producing wells. In the year 2010-2011, Songo Songo field experienced an increase in additional reserves due to improvement in the recovery factors. On Gross Company basis, there has been a 27 % increase in Songo Songo's proven additional natural gas reserves with total additional gas production of 17.5 Bcf. Figure 3.7 shows that Songo Songo field has been expanding its capacity to extract natural gas from its existing five wells over the years. The increasing production has further been attributed to high demand of natural gas to generate electricity.



**Figure 3.6 Natural gas production at Songo Songo and Mnazi Bay fields**

Source: TPDC (2014b)

Mnazi Bay field extracts natural gas, which is mainly used for power generation in the Southern regions of Tanzania. As figure 3.7 indicates, between 2007 and 2014, production was increasing slowly compared to the Songo Songo field. Currently, this field is running below its capacity. From mid-2015, it is anticipated that the production will further increase after construction of new pipeline of 36” inches for commercial transportation of natural gas (TPDC, 2013).

### 3.6.2 Natural Gas Consumption

The natural gas produced in Tanzania is consumed as a source of power generation into the national grid and as power to various industries. All these bring inter-sectorial linkages and additional source of government revenue from natural gas resource. Recently, the use of natural gas has accelerated industrial growth and it has helped to reduce power crisis in the

country. Natural gas utilization is cheaper compared to liquid fuels as it involves lower per unit cost to generate power compared to other forms of fossil fuels like oil.

### **3.6.3 Power System and Electricity Supply**

Songo Songo and Mnazi Bay natural gas fields injected about 424 Megawatt (MW) of power generation which is equivalent to 40% of total energy input into the national grid in 2013 (EWURA, 2013). The electricity generation costs between 6 and 8 USD for every Kilowatt (kWh) produced (TPDC, 2013). Natural gas is also used for power generation in the southern regions where the power station is not yet connected to the national grid. Somanga Fungu gas powered plant supplies power to southern regions to people living along the gas pipeline. The gas powered plant has installed capacity of 7.5 MW but the maximum demand to date is 2.43 MW.

The major existing pipeline has about 532 km and potential capacity of transmitting about 103 (mmscf) of gas, supplying to Dar es Salaam city .Table 3.3 shows power generated for different uses using natural gas resource. The generated power for electricity is processed through various gas powered plants which are managed by the Tanzania Electricity Supply Company (TANESCO). Natural gas for industrial uses is transmitted by pipelines direct to industries for their immediate consumption.

Mnazi Bay field uses gas to produce about 300 MW of electricity to supply the southern regions. About 80% of Songo Songo plant's output, generates electricity to the national grid. The plant has installed capacity of about 370 MW in 2014.

Currently, the construction of one of four power plant complex, namely Kinyerezi III gas powered power plant is underway. The plant is built in Kinyerezi area in Dar es Salaam to expand power generation in the country. The project comprises the initial installation of

180-MWh to 300 MWh units upon first phase completion at the end of 2015. The construction of Kinyerezi III power plant is expected to curb the recurrent power shortages in the country and reduce dependency on hydropower and heavy fuel based generations which are expensive compared to gas usage. The generated power from the Kinyerezi III plant will be directed to a 400-KV substation and then connected to the national grid. TANESCO designed a power plant development plan with the aim of establishing a sustainable basis for energy access and to improve electricity supply and provision in the country.

**Table 3.3 Natural gas consumed for Electricity generation into national grid and power to industries**

Years	TANESCO		Industrial power		Total MWh generated
	Gas input (mmscf)	Electricity generated (MWh)	Gas input (mmscf)	Power generated (MWh)	
2004	8,275.13	249.9	1527.01	46.12	296.02
2005	14,505.61	438.06	2671.52	80.68	518.74
2006	13,518.27	408.25	3244.34	97.98	506.23
2007	17,031.63	514.35	3039.46	91.79	606.14
2008	18,553.14	560.30	4099.12	123.79	684.09
2009	22,259.84	672.25	5418.99	163.65	835.90
2010	24,310.73	734.18	5048.32	152.46	886.64
2011	31,221.70	942.91	5028.81	151.87	1094.78
2012	31,576.93	953.62	7677.27	231.85	1185.47
2013	28,284.98	854.21	6030.42	182.12	1092.04
2014	13,839.19	414.94*	2191.13	66.17*	481.11*

(\*) Calculation involves only six months due to available data

Source: Author's calculation using data from TPDC

## CHAPTER FOUR

### METHODOLOGY

#### 4.0 Introduction

This chapter presents the methodology of the study. Section 4.1 highlights the basic theoretical model of exhaustible resources which is Hotelling model and shows its dynamic optimality conditions. Section 4.2 focuses on empirical framework and econometric model employed to empirically test the relevance of dynamic optimality conditions under Hotelling's model. It also discusses the estimation technique used. Section 4.3 concentrates on simulation using Excel Solver spreadsheet to obtain the optimization path. Section 4.4 provides Diagnostic tests. Section 4.5 shows the data utilized, study area and their measurements and lastly section 4.6 provides a summary of the chapter.

Firms in oil and gas industry have costs that pertain to the field level in the production of their products. These costs are not fixed and vary according to production stages and across firms. The costs of producing natural gas are mostly related at the upstream section where extraction is done. The costs related to upstream section include exploration, development and operating costs or lifting costs. For the purposes of analysis, this study only considers the operation costs for natural gas extraction.

We follow the theoretical framework developed by Halvorsen and Smith (1991) and Chermak and Patrick (2001): (2007). Principally, these studies derived the extended form of Hotelling's dynamic conditions and later estimated the indirect cost functions with various restrictions using duality theory. The studies, however differ in the type of resource tested, the level of aggregation over time, resource deposits, the specification of the final

price path, parameters estimated as well as estimation techniques. To achieve its set objectives, this study intends to fill in the literature gap, in the natural gas optimization path which was not captured by studies done by Halvorsen and Smith (1991) and (Chermak and Patrick 2001: 2002 and 2007).

The study assumes an extraction path under the competitive market situation, technological level is known and the analysis is performed under conditions of certainty. We also assume the natural gas firm is a cost minimizer in order to obtain the estimates of shadow price as was also assumed in the study done by Halvorsen and Smith (1991).

Cobb- Douglas indirect cost functions in the form of Unrestricted, restricted and Gross cost functions are specified. We employ panel feasible generalized least squares (FGLS) econometric estimation technique to achieve the first objective of estimating extraction cost and shadow price and panel data for the second objective of testing Hotelling's theory. Specifically, FGLS technique is used to estimate the parameters of natural gas extraction cost model and replicate our analysis using either fixed effects or random effects models. By using restricted indirect cost function, the shadow price for natural gas in Tanzania is also estimated.

Our study accomplishes second and third objectives of testing the Hotelling's principle and simulating the optimization path using a discount rate of 8%. The choice of discount rate for investment and environmental projects has far not been simple and it suffers controversy in the way the rate is privately or socially determined. In many cases, the choice of discount rate is equated with the market rate of interest and the rate of return on investments, after lending or borrowing at bonds or money markets (Perman *et al*, 2003). Basically, discount rates are equated by the market rate of interest for social decision

making. In practice, economists argue that it is important to use a higher rate of return on investments even if the market rate of interest is lower. Therefore, Perman *et al* (2003) suggested that, for social decision making and environmental projects, someone should look at a higher discount rate more than 8%. Thus, in practice, the choice of 8% discount rate used in the study reflects, among other things the firm's cost of international borrowings and lending such as from multilateral institutions, money markets and international banks and market interest rate. This is because the choice of discount rates for investments and environmental projects matters a lot. The chosen rate can affect the firm and the institution's decision making and regulatory policy. However, according to Zhang *et al*, (2007) there are variations in a way the discount rate is chosen between developed countries and developing countries. Developed countries, practice lower public discount rate between 3% to 7% whereas the developing countries apply higher social discount rates ranging from 8 % to 15%. These variations are largely due to different theoretical approaches to the choice of discount rate adopted by different countries. The choice also considers economic efficiency as well as intergenerational equity.

Furthermore, the choice of the social discount rate differs around the world. The choice highly depends on own country projects, individual agencies, multilateral development banks and firms projects, for which each institution has different approach in choosing most appropriate social discount rate for its various projects. Traditionally, the World Bank (WB) has not calculated a social discount rate for its various investment projects. But the bank approach has used 10% to 12% as a notional figure for cost benefit analysis (Zhang *et al*, 2007). The World bank notional discount rates have been used in many developing countries for various projects undertaken or projects funded by the World bank.

To achieve the second objective, the Hotelling's dynamic optimality condition is presented in econometric form and estimated using panel data and using either Random effects (RE) or fixed effects (FE) models. The condition is then tested with and without parametric restriction using Hausman (1978) specification test for all specified indirect cost functions at discount rates of 8% and sensitivity analysis is conducted for other discount ranges between 1% to 20%.

The third objective is obtained by using the linear programming framework, to simulate and obtain the natural gas optimal extraction path for each firm. The excel spreadsheet solver is used for optimization at 8% discount rate also. The resource optimization process is significant in the following aspects. It shows the value of the extraction costs that ensures the resource optimal path. It also describes how the resource was extracted over time. All of them help in policy discussions and matters pertaining to conservation and sustainability of the resource. Our study conducts the sensitivity analysis to ascertain the effects on the optimization path when discount rate of 8% is varied with two different points, such as 6% as lower and 10% as higher discount rate respectively.

#### **4.1 The Theoretical Framework of Hotelling's Rule**

The theoretical framework that underpins the theory of nonrenewable resources is the basic Hotelling's Rule. Hotelling (1931) assumes economically rational, wealth maximizing behavior on the part of all agents involved. According to Hotelling (1931) a profit maximizing firm will adjust the resource production, so that the difference between price and marginal cost will rise at the rate of discount,  $(P - MC) = \rho$ , where P is the price of resource, MC is the marginal cost of extracting the resource and  $\rho$  is the discount rate. The

framework presented below is according to the basic and extended theoretical model of the Hotelling Rule as presented by Chermak and Patrick (2001).

Further, Hotelling's model assumes a perfect competitive market situation, technological level is known and there are no uncertainties.

Chermak and Patrick (2001 and 2002) explained that the natural gas firm's profit maximizing equation is presented subject to the effect of extraction production capacity constraint and traditional resource stock constraint.

Let  $R(t)$  denote the current quantity of remaining gas reserves in the field. And  $C(q(t), R(t))$  denote the cost function for gas extraction.

Assuming maximum production at  $t$ ,  $Q(t) = Q(\mathbf{q})$ , where  $\mathbf{q} = q(t)$  and  $t \in (0, T)$ , it is the gross production at time  $t$ . For each maximum production at  $t$ ,  $Q(t)$ , at  $t \in (0, T)$  may be affected by previous gross production levels, which are  $q(t)$  for all  $t \in (0, T)$ .

$R(t)$  is the stock of reserves, and it is a state variable which is continuous differentiable, defined as  $t \in (0, T)$  on a time interval.

Let  $\delta Q / \delta q(t) = \tilde{A}_q Q$ , the stock of the resource at time  $t = 0$  which can be written as;

$$R(0) = \int_0^T Q(\mathbf{q}, t) dt \dots\dots\dots (4.1)$$

The initial stock level will differ with the chosen production path except  $q(t) = Q(\mathbf{q})$  for all  $t \in (0, T)$ . Equation (1) shows that the remaining stock at any time  $t$  is;

$$R(t) = \int_0^T Q(\mathbf{q}, t) dt - \int_0^t q(x) dx \dots\dots\dots (4.2)$$

The transition equation on the resource stock is;

$$\dot{R}(t) = S(\mathbf{q}) - q(t), \quad R(T) \geq 0, \dots\dots\dots (4.3)$$

$S(\mathbf{q})$ , is the effect of past production on recoverable stock,

$$S(\mathbf{q}) = \int_0^T (\tilde{\mathbf{A}}_q \mathbf{Q} \tilde{\mathbf{A}}_t \mathbf{q} + \mathbf{Q}_t) dt \leq 0. \dots\dots\dots (4.4)$$

Equation (4.3) is for specific pressure produced resources such as oil and natural gas which follows from reservoir engineering theory.

Let  $q(t) = g(\mathbf{U}^g, R, t)$  represents the gross production process where  $\mathbf{U}^g = \{u_j(t): j=1, \dots, J\}$  are *inputs* into the gross production process. The *final production* of natural gas which is the amount that is *input into the pipeline* to be transported to consumers is given as  $z(t) = f(\mathbf{U}^f, q, t)$  where  $\mathbf{U}^f = \{u_k(t): k=1, \dots, K\}$  are inputs used to process gross production to get the final product at each time  $t$ ,  $z(t)$ . Where by the final production cannot exceed gross production  $z \leq q$ .

Duality theory is generalized from the consumer and the theory of the firm. According to Diewert (1974), Duality theory enables a derivation of systems of demand equations which are consistent with maximizing or minimizing behavior of an economic agent, by differentiating a function rather than solving a constrained maximization or minimization problem. Also, the advantage of duality theory helps in deriving the comparative statics theorems originally presumed from maximizing behavior. For example, production function determines cost function given certain conditions and in opposite way also, the cost function determines production function given certain conditions, and therefore we have duality between cost and production functions.

The dual applies here where the gross cost function is dual to the gross production function before the firms maximize profit.

*Definition of variables used to be used on equations below:*

Let  $W^k = \{ w_k(t): k= 1, \dots, K\}$  be the processing inputs prices,

$U^k$  = processing inputs

$W^g = \{ W_g(t): j= 1, \dots, J\}$  are prices of inputs into gross production function,

$U^g$  = gross production inputs

$R(t)$  = remaining stock of natural gas

$q$  = gross production of natural gas

$Q$  = is a natural production, based on the current reservoir pressure

$t$  = time

$P$  = output price

$z$  = final production

$C$  = Cost

The gross cost function can be written as :

$$C(W^g, q(t), R(t), t) \equiv \min_{U^g} W^g U^g \text{ subject to } q = g(U^g, R, t). \dots\dots\dots (4.5)$$

The firm's problem now is to choose the input production paths  $U^k$ , the gross production path  $q(t)$  and production time to maximize profits,  $(\pi)$ . Where  $P(t)$  is the output price per unit of final production,  $z(t)$ . Therefore we maximize profit as:

$$\text{Max } \pi = \int_0^T [P(t) z(t) - W^k \cdot U^k - C(W^g, q(t), R(t), t)] e^{-rt} dt, \dots\dots\dots (4.6)$$

Subject to the resource constraint and bounds on gross production at any time  $t$ ,

$$0 \leq q(t) \leq Q(q), \dots\dots\dots (4.7)$$

The upper bound on periodic production,  $Q$  is a natural physical constraint, based on the current reservoir pressure. Initial reservoir pressure is a function of formation characteristics and depth of the well. As soon as extraction commences, the upper bound

falls overtime due to lessening reservoir pressure. The rate of fall in pressure is affected by previous productions. In procedure,  $Q$  and  $R$  are integrated into economic model through reservoir engineering theory.

Then the Hamiltonian function for the firm problem is;

$$H(t) = [ P(t) z(t) - W^k \cdot U^k - C(W^g, q(t), R(t), t) ] e^{-rt} + \lambda [ S(q) - q(t) ] \dots\dots(4.8)$$

Where  $\lambda$  is the multiplier of resource price on the transition equation of the resource stock.

The first order necessary conditions according to maximum principle are;

$$\text{Condition 1; } \quad \frac{\delta H}{\delta R} = -L_R = \dot{\lambda} = e^{-rt} C_R, \dots\dots\dots(4.9)$$

Where,  $C_R$  marginal cost of extracting the remaining stock of reserves,  $r$  is the discount rate and  $t$  is time.

Equation (4.9) is a condition according to maximum principle. The condition presents the value of dynamic optimality condition for exhaustible resources. This condition will be inter-grated into the econometric model to test the relevance of Hotelling model.

The econometric model will be developed from the first condition outlined on equation (4.9). This then will be used empirically to estimate the shadow price of the natural gas resource and test the Hotelling's principle in the theory of exhaustible resources. The dynamic optimality condition for exhaustible resources from the equation (4.9) can be written in the current value form as:

$$\dot{m} = rm - L_R = rm + C_R \dots\dots\dots(4.10)$$

Where  $m \equiv e^{rt} \lambda$  is the current value shadow price (in-situ),  $m(t) \geq 0$  for all  $t = (0, T^*)$  because  $m(t) \equiv e^{rt} \lambda(t)$  then  $\lambda(t) \geq 0$  for all  $t = (0, T^*)$ .

### **Interpretation;**

Equation (4.10) above explains that, the current value shadow price for the resource rises at discount rate less the future increase in costs from marginal unit of extracting the natural gas resource. The equation also provides the empirical test of the theory and shows the dynamic behavior of natural gas producing firms which necessitates the estimation of *shadow price*  $m$ , *marginal reserve costs*  $C_R$  of extracting the resource from the ground given the level of *discount rate*  $r$ .

For the estimation of *optimal shadow price* of the resource and *cost of extracting* the resource, we consider the cost minimization problem of producing levels of gross and final product. Let  $q = \bar{q} = q^*$  and  $z = \bar{z} = z^*$  be profit maximizing levels of gross and final output respectively.

The Lagrangian for the problem is;

$$\bar{L} = \mathbf{W} \cdot \mathbf{U} + \gamma [\bar{z} - f(\mathbf{U}^f, \bar{q}, t)] + \delta [\bar{q} - g(\mathbf{U}^g, R, t)] + \rho (Q - \bar{q}) \quad \dots\dots\dots (4.11)$$

Where  $\gamma$  is a multiplier on *final production* constraint,  $\delta$  is a multiplier on *gross production* constraint and  $\rho$  is the multiplier on *physical capacity* constraint. The above Lagrangian problem is solved to obtain the necessary conditions.

Then the cost minimization (4.11) produces the indirect final cost function of this form,

$$\bar{C}(\mathbf{q}, z, R, \text{inct}, \text{roy}, \dots\dots). \quad \dots\dots\dots (4.12)$$

Following the indirect cost function in (4.12) above, we measure the *shadow price* of the resource by applying the *envelop theorem* as was also used by Halvorsen and Smith (1991) on the average cost function. Solving for the cost minimization and employing the envelop theorems yields the lemma/proposition below:

**LEMMA ONE;** *the resource current value shadow price is equal to the negative of the marginal final cost of gross production or*  $m = - \bar{C}_q$

The lemma above is used in this study to calculate the shadow price. The Lemma is interpreted as follows, holding other factors constant; the additional gross production reduces the marginal extraction cost of producing a given level of final product. It also means that the current value shadow price can be found by differentiating the estimated indirect final cost function with respect to gross production function,  $q$ .

Therefore it is observed that  $m(\text{shadow price})$  and  $C_R(\text{marginal cost in respect to extracting natural gas reserves})$  which are needed in testing equation (4.10) of the dynamic optimality, can be obtained by econometrically estimating the indirect final cost function in equation (4.12) and differentiating it with respect to  $q$  and  $R$ . Where  $q$  and  $R$  are gross production and remaining stock of gas reserves respectively.

Since the estimated indirect gross and final cost function are statistically independent, equation (4.12) can be differentiated and solved to give a more precise and suitable form for testing the dynamic optimality condition.

The dynamic optimality from equation (4.10),  $\dot{m}(t) = rm(t) + \bar{C}_R(t)$  can also be written as follows as a result of Lemma 1 ( $m(t) = -\bar{C}_q$ ):

$$\bar{C}_R = [-\bar{C}_{qt} + (1+r)\bar{C}_{qt-1}] \dots\dots\dots (4.13)$$

Where;

$$m(t) = -\bar{C}_q = \frac{\partial \ln \bar{C}(t)}{\partial \ln q(t)} \dots\dots\dots (4.14)$$

It is the marginal cost in respect to gross production of gas. This expression is also used to calculate the shadow price.

The expression (4.13) is dynamic optimality condition in equation (4.10). It is used in parametric restriction of indirect cost function in (4.12) together with discount rate ranges in econometric testing of Hotelling's rule as a theory of nonrenewable resources, Chermak and Patrick (2001).

Now, we proceed to describe how the cost functions are expressed and estimated. And later the econometric model used to test the dynamic optimality condition under Hotelling's framework is provided.

#### **4.2 The Empirical Framework and Estimation Techniques**

For the purpose of analysis, we consider both the theoretical and the empirical models that have been employed in previous literature.

To achieve objective one of estimating the firm's extraction cost and shadow price, a panel data estimation technique is used. This section also shows the estimated cost functions as derived from both Hotelling's framework and duality theory.

The natural gas extraction cost model depends on gross production quantities from gas wells, refined natural gas quantities, fields remaining reserves, and government policy instruments like income taxes and royalties. The data are presented on a monthly basis and for two natural gas fields. It is acknowledged that there is heterogeneity in physical, technological and production characteristics of both operating fields. Blackorby and Schworm (1982), examined data aggregation scenarios for separate resource reserve and single resource reserve with extracting firms. They found that the aggregation may not be able to replicate the actual behavior of firms extracting from different reserves with different technology.

### 4.2.1 The Theoretical Model

According to Baltagi (2008) the panel data regression can be expressed as

$$c_{it} = \alpha + X_{it}'\beta + u_{it} \quad \dots\dots\dots (4.15)$$

Where  $i=1, \dots, N$ :  $t=1, \dots, T$

With  $I$  denoting firms and  $t$  denoting time,  $C_{it}$  measures the firm's extraction costs and  $X_{it}$  measures related items that have effects on the cost and production of natural gas. He further explained that, most panel data applications employ a one way error component model for the disturbance with

$$u_{it} = \mu_i + v_{it} \quad \dots\dots\dots (4.16)$$

Where  $\mu_i$  denotes unobserved firm's heterogeneity and  $v_{it}$  is the common error term. The  $\mu_i$  is time invariant and is taking care of any firm's unobserved effects that is not included in the regression model. The common error term varies with firms and time. The unobserved variables can be included in the regression model as individual dummies to estimate the unobserved effects.

The panel data estimation can be described in panel generalized least square technique, Fixed (FE) or Random effects (RE) models. To choose either RE or FE model for estimation, the Hausman Specification Test (1978) is used.

### 4.2.2 The Econometric Model

The cost function is specified in the form of generalized Cobb-Douglas Cost function. For the purpose of this study, the Cobb-Douglas cost function is used because it is comparable to other flexible functional forms like trans-log to avoid an excessive number of parameters as it would be required in the flexible functional forms. Also, the potential problem of multicollinearity between the regressor's if it appears to have strong correlation

is avoided. The costs functions are controlled for unobserved firm's heterogeneity in a gas reservoir like reservoir geology and rocks formations.

The data used for panel model estimation is an aggregation of all costs relating to natural gas extraction for each firm to estimate the unrestricted and restricted cost functions. The natural gas extraction cost empirical models estimated by panel technique are;

*Unrestricted indirect cost specification written as (FC<sub>U</sub>);*

$$\ln \bar{C}_{it} = \sum_{i=1}^N \alpha_i D_i + \sum_{yt=1}^Y \alpha_y D_y + \beta_q \ln q_{it} + \beta_z \ln z_{it} + \beta_R \ln R_{it} + \beta_{inct} \ln inct_{it} + \beta_{roy} \ln roy_{it} + e_{it} \quad \dots \dots \dots (4.17)$$

Where  $i = 1, \dots, N$  firms dummy variable,  $y = 1, \dots, Y$  months in a year,  $D$  is dummy variable and  $e_{it}$  = error term

Where  $\alpha_i$  captures individual unobserved heterogeneity. It is constant over time and different across units, and  $e_{i,t}$  is an error component changing both over time and across firms.

In all cases, the major assumption is that, unobserved individual heterogeneity  $\alpha_i$  and error term  $e_{i,t}$  are uncorrelated for all  $i$  entities and  $e_{i,t}$  is uncorrelated overtime.

The variables are in natural logarithm.

$\bar{C}$  is the monthly production cost which is a dependent variable,  $\alpha_i$  is unobserved firm's effects. The explanatory variables are,  $q$  which is the logarithm of gross natural gas output,  $z$  is the logarithm of refined natural gas quantities,  $R$  is the logarithm of remaining natural gas reserves at the field,  $inct$  is the logarithm of income tax and  $roy$  is logarithm of royalties charged to the firm.

The unrestricted cost function is estimated as full model without any constraint on the parameters.

$$\ln \bar{C}_{it} = \sum_{i=1}^N \alpha_i D_i + \sum_{y=1}^Y \alpha_y D_y + \beta_q \ln q_{it} + \beta_q \ln z_{it} + \beta_R \ln R_{it} + \beta_{inct} \ln inct_{it} + \beta_{roy} \ln roy_{it} + e_{it} \dots \dots \dots (4.18)$$

*Estimation of Restricted final cost function (FC<sub>R</sub>).*

The restricted final cost function restricts the parameter estimates on the final and gross production to be of opposite sign but equal in absolute value such that  $\beta_z = -\beta_q$

$$\ln \bar{C}_{it} = \sum_{i=1}^N \alpha_i D_i + \sum_{y=1}^Y \alpha_y D_y + \beta_q \ln q_{it} - \beta_q \ln z_{it} + \beta_R \ln R_{it} + \beta_{inct} \ln inct_{it} + \beta_{roy} \ln roy_{it} + e_{it} \dots \dots \dots (4.19)$$

*An indirect final cost function (FCA) is estimated, with restriction that final production, (lnC – lnz)*

$$\ln \bar{C}_{it} - \ln z_{it} = \sum_{i=1}^N \alpha_i D_i + \sum_{y=1}^Y \alpha_y D_y + \beta_q \ln q_{it} + \beta_R \ln R_{it} + \beta_{inct} \ln inct_{it} + \beta_{roy} \ln roy_{it} + e_{it} \dots \dots \dots (4.20)$$

*An indirect gross cost function (GC) is estimated, with restriction that final production z=0,*

$$\ln \bar{C}_{it} = \sum_{i=1}^N \alpha_i D_i + \sum_{y=1}^Y \alpha_y D_y + \beta_q \ln q_{it} + \beta_R \ln R_{it} + \beta_{inct} \ln inct_{it} + \beta_{roy} \ln roy_{it} + e_{it} \dots \dots \dots (4.21)$$

The final cost functions (4.17), (4.18) and (4.19) are applied as empirical specifications of equation (4.12), while the gross cost function (4.21), is employed for empirical specification of equation (4.5). By differentiating the resulting final cost specification with respect to  $q$  and  $R$ , applying the first lemma derived above, and substituting into (4.13) gives us the parametric form of the dynamic optimality for the final cost models. The final cost function will be characterized by  $\bar{C}_z \geq 0$ ,  $\bar{C}_q \leq 0$ , and gross cost function, characterized by  $\bar{C}_q \geq 0$  according to the theory developed above. This indicates that the

estimated parameters would be  $\beta_z \geq 0$ ,  $\beta_q \leq 0$  for final costs, and  $\beta_q \geq 0$  for the gross costs regression model, Chermak and Patrick (2001),

We expect that the shadow price to be relatively higher when gross production and its marginal costs are declining for every unit (in *mmscf*) produced.

#### **4.2.3 Estimation Technique**

A Panel data analysis is used in this study to achieve the first and second objectives. We first estimate the panel regression of specified extractions costs models using panel data Feasible Generalized Least Square (FGLS) estimation and check robustness of results by employing either random (RE) or fixed effects (FE) models. Later, Hotelling's dynamic optimality condition is tested.

A panel dataset is a type of dataset where behavior of entities is observed across time. Panel data analysis deals with individual heterogeneity and controls for unobserved variables that change overtime. These are Random effects (RE) and fixed effects (FE) models. When modelling data that are grouped in terms of years and number of entities, a common approach is to employ Hausman test which help to decide and choose between random and fixed effects models. Also the test shows how significantly parameter estimates differ among each other on the models.

The rationale behind choosing the panel data estimation is due to its offered benefits compared with the other estimation techniques. The panel estimation provides more degree of freedom in analysis; the dataset comprises both cross sectional and time series dimensions. It also controls for unobserved individual effects within the firm over time as well as across the entity over time.

#### 4.2.3.1 Panel data Feasible Generalized Least Square (FGLS) Technique

To achieve objective one of estimating natural gas extraction costs, we perform panel FGLS estimation technique. This technique is desirable in control and correction of problems related to heteroskedasticity and autocorrelations in the panel data models.

Essentially, failure to account for individual heterogeneity in the model, forces the mean of the dependent variable to be equal hence leads to biased parameter estimates under Ordinary Least Square (OLS). Also, it can induce omitted variable bias leading to inconsistent estimators (Hsiao, 2003). Since the Ordinary Least Square technique basic assumption indicates that the explanatory variable must be exogenous,  $E[\varepsilon_t X] = 0$  (Wooldridge 2008). Thus, the explanatory variables should be uncorrelated with the error term. Verbeek (2004) described that, sometimes the regressor's can correlate with error term due to simultaneity, omitted variables, measurement errors or endogeneity of the explanatory variables. Consequently, as a result of omitted variable bias and failure to account for unobserved heterogeneity, OLS estimator is considered to be biased and inconsistent, and thus we need to look for another estimator that can overcome the challenges mentioned.

According to Baltagi (2008) the strict assumptions of homoscedasticity and no serial correlation applies in conducting FE or RE models. Furthermore, Wooldridge (2002) and Greene (2003) ascertain that, parameter estimates produced by FE or RE are basically inconsistent and inefficient in the existence of autocorrelation and heteroskedasticity in the model. As a result, the model needs to be adjusted or transformed to obtain the parameter estimates which are Best Linear Unbiased Efficient (BLUE). Therefore OLS is applied to the transformed model of panel data to obtain unbiased and efficient parameter estimates.

The process of utilizing OLS to a transformed panel model is what is referred as panel Feasible generalized Least squares (FGLS) technique.

Thus, this study seek to address some of the challenges identified above by opting to employ the feasible generalized least square of panel data to estimate the parameters of specified cost functions and to test the Hotelling's framework. The panel data estimation also provides strict exogeneity assumptions for models that contain unobserved firm's effects (Wooldridge, 2008). Panel data FGLS estimation is desirable and appropriate technique to overcome problems related to autocorrelation, heteroskedasticity, omitted variables cases and multicollinearity found in either FE, RE or OLS models.

The study also conducts robustness check for its estimation results. The results obtained using panel FGLS model are checked by replicating the analysis using fixed effects (FE) or Random effects (RE) depends on Hausman statistics test results. The reason behind adopting the FE or RE regression models is to compare the precision of our results obtained under FGLS regression model.

#### **4.2.3.2 Fixed Effects (FE) Model**

A fixed effect (FE) model examines group differences in intercepts, assuming the same slopes and constant variance across entities. FE allows for correlation between the regressors and the firm's heterogeneity. Fixed effects estimators depend on deviations from their group means which is sometimes known as within-groups estimators (Davidson and MacKinnon, 1993). The FE model can be specified as;

$$y_{it} = X'_{it} \beta + \alpha_i + v_{it} \dots\dots\dots (4.22)$$

Where  $\alpha_i$  is included as unobserved and observable effects and specifies an estimable mean.  $X'$  is a vector of explanatory variables,  $y_{it}$  is the dependent variable and  $v_{it}$  is the common error term. The fixed effects model takes  $\alpha_i$  to be a group-specific constant term in the regression model. The fixed effect does not vary over time (Greene, 2003).

The fixed effects model is a suitable if someone is dealing with a specific set of N firms. Then, the unobserved firms' effects are assumed to be fixed parameters estimated and the error term is stochastic with  $v_{it}$  being independent and identically distributed *i.i.d*  $(0, \sigma_v^2)$ . Also the regressors  $X_{it}$  are assumed to be independent of error term  $v_{it}$  for all  $i$  entities and time  $t$ . Under FE, the partial effects can be consistently estimated in the presence of time invariant omitted variables that can be related with explanatory variables. Hence, it makes fixed effects to be robust than random effects.

To determine the use of FE or RE, we perform Hausman specification test. The time invariant variables are taken out by deviations from mean transformation in FE. The FE estimator becomes efficient when  $T \rightarrow \infty$ .

If the standard Hausman tests rejects the null hypothesis that the conditional mean of the error term given the regressors is zero then fixed effects estimators are consistent and is an appropriate model. Therefore, the fixed effects will be the preferred model if the errors are correlated with the regressors but the null hypotheses does not.

#### **4.2.3.3 Random Effects (RE) Model.**

A Random effect model assumes that a common mean value for the intercepts exists and the cross-sectional differences in the intercept values of each natural gas firm are reflected in an error term. This means that under random effects, the regressors are not correlated with firm's effects. The RE is considered as a regression model with a random constant

term (Greene, 2003). Hence RE assumes that the firms' heterogeneity is not correlated with the explanatory variables of the model. If there are differences across firms that have an influence on the dependent variable then RE is a preferred model.

When the unobserved firm heterogeneity is assumed to be uncorrelated with explanatory variables, then the random effects model is in this form;

$$y_{it} = X'_{it} \beta + \alpha_i + v_{it} \dots\dots\dots (4.23)$$

The random effects models considers  $u_i$  as a group specific random element which is similar to error term  $v_{it}$  except that, for each group it enters the regression identically in each period.

The random effects model also exploits the serial correlation in the error term,  $v_{it} = \alpha_i + u_{it}$  in a generalized least squares (GLS) framework. To ensure GLS is consistent, the strict exogeneity between regressors and the error term is needed. Therefore RE is a feasible GLS estimator as well (Wooldridge, 2008).

When the firm's effects are strictly uncorrelated with explanatory variables, then it could be appropriate to model the firm's specific constant term as randomly distributed across sectional units (Greene, 2003).

The random effects treat the decomposed error term as normally distributed with mean zero and estimable variance. Essentially, RE is considered to be appropriate if the firm dimension N is large relative to T dimension, such that the firm effects are viewed as random. RE also gives an advantage of using time invariant explanatory variables. According to Hsiao (2003) RE model is a specific case with zero correlation. Thus RE, is widely used in the analysis of panel data with large N relative to T.

FE model allows for endogeneity of all regressors with individual effects (Chamberlain 1984), while RE looks at exogeneity of all regressors (Mundlak 1978). The choice of random effects ahead of fixed effects also depends on the results obtained from Hausman specification test. If we fail to reject the null hypothesis of the conditional mean of the error term given the regressors is zero, then there is no difference between random and fixed effects models. Thus the RE model will be chosen and considered to be an appropriate model in this case.

Similarly, to accomplish objective one, we estimate natural gas shadow price in Tanzania. We calculate natural gas shadow price using the estimated restricted cost function specified in equation (4.21). We estimate the regression equation (4.21) using FGLS technique and perform a partial differential in respect to natural gas gross output  $q$ . The formula below helps us to obtain the observable measure of shadow price. Shadow price shows how the resource is scarce over time as well as its appreciation on the ground before and after resource extraction. It is also a crucial component for policy purpose regarding setting of market prices for most natural resources in the world today. In this case we are calculating shadow price which is important for resource rate of appreciation, as well as for setting and designing domestic and international natural gas price in Tanzania.

Shadow price is calculated as result of Lemma 1, shown above. After estimating our FCR regression model, we are performing the derived formula below to obtain the observable shadow price for natural gas resource in Tanzania.

$$m(t) = -\bar{C}_q = \frac{\partial \ln \bar{C}(t)}{\partial \ln q(t)} \quad (4.24)$$

## Objective 2.

### 4.2.4 Testing the Hotelling's Principle

In line with objective two outlined, we are also testing Hotelling's dynamic optimality condition at 8% discount rates and sensitivity analysis done with other discount rates ranging from (1 % to 20%) as also used by Halvorsen and Smith (1991) and Chermak and Patrick (2001).

The study uses the dynamic optimality condition (4.13) to restrict the parameters of indirect final cost functions. Such that equation (4.12) which provides the econometric estimation of the regression equations in (4.17) (4.18) and (4.19) is restricted with the dynamic optimality condition. Basically, we want to test that the dynamic optimality condition in equation (4.13) is satisfied by our parameter estimates of equation (4.12)  $\bar{C}(\mathbf{q}, z, R, inct, roy, \dots)$  under null hypothesis. And under alternative hypothesis, the dynamic optimality condition is not satisfied by parameter estimates of equation (4.12).

Therefore we are estimating  $\bar{C}(\mathbf{q}, z, R, inct, roy, \dots)$  with restriction inferred by dynamic optimality condition and without the implied condition. In other words, we are estimating equation (4.12) that provides our indirect final cost functions without restriction and then estimate the same equation subject to dynamic optimality condition implied in equation (4.13). We call the former equation without restriction as unconstrained, while the latter is constrained equation due to imposed restriction. The Hausman test performs the test by comparing the constrained as FE model and unconstrained cost functions to be RE model after their estimation.

Chermak and Patrick (2001) and Patrick (2015) developed the procedure for nonlinear regression model to become a linear parameter model and be able to estimate the model and as well as testing the theory.

The unrestricted final cost function in the form of generalized cobb-Douglas function is written as;

$$\bar{C} = \beta_0 z^{\beta_1} q^{-\beta_1} R^{\beta_3} inct^{\beta_4} roy^{\beta_5} e^\varepsilon \dots\dots\dots (4.25)$$

The unrestricted indirect cost function above (4.25) is restricted by dynamic optimality condition following Lemma 1 developed above (page 65), and the resulting restrictions in equation (4.13).

$$-\bar{C}_{qt} = - (1+r)\bar{C}_{qt-1} + \bar{C}_R \quad (4.13)$$

Where  $r$  = discount rates,  $\bar{C}_R$  is the estimated marginal cost with respect to remaining reserves,  $\bar{C}_q$  estimated marginal cost function with respect to quantities and  $\bar{C}_q$  equals  $m(t)$  which is shadow price .  $\bar{C}_{qt-1}$  is the lagged value of the estimated cost function.

Equation (4.25) and dynamic optimality condition yields the following restricted cost function that is used in testing the consistent of data with theory.

The restricted form of indirect cost function (4.25) is written as;

$$\ln \bar{C}_t = \ln \beta_0 + \ln \left[ \frac{\beta_1 (1+r) z^{\beta_1} q^{-\beta_1} R^{\beta_2} inct^{\beta_3} roy^{\beta_4}}{\beta_1 R_t - \beta_2 q_t} \right] + \varepsilon_{t-1} \dots\dots\dots (4.26)$$

or

$$\ln \bar{C}_t = \beta_0 + \ln \left[ \frac{\beta_1 q_t R_t (1+r)}{q_{t-1} (\beta_1 R_t - \beta_2 q_t)} \right] + \beta_1 \ln \left( \frac{Z_{t-1}}{q_{t-1}} \right) \ln q_{t-1} + \beta_2 \ln R_{t-1} + \beta_3 \ln$$

$$inct_{t-1} + \beta_4 \ln roy_{t-1} + \varepsilon_{t-1} \dots \dots \dots (4.27)$$

Where by,  $\beta_0$  represents dummy variables and constant term.

The linear Taylor series approximation to above (27) can be written as ;

$$\ln \bar{C}_t \cong$$

$$\beta_0^0 + \ln \left[ \frac{\beta_1 q_t R_t (1+r)}{q_{t-1} (\beta_1 R_t - \beta_2 q_t)} \right] + \beta_1^0 \ln \left( \frac{Z_{t-1}}{q_{t-1}} \right) \ln q_{t-1} + \beta_2^0 \ln R_{t-1} + \beta_3^0 \ln$$

$$inct_{t-1} + \beta_4^0 \ln roy_{t-1} + \sum_{k=0}^5 \frac{\delta \ln \bar{C}_t}{\delta \beta_k^0} (\beta_k - \beta_k^0) + \varepsilon_{t-1} \dots \dots \dots (4.28)$$

where  $\beta_k^0$ , are the initial values for the parameters. The initial values correspond to parameter estimates from unrestricted indirect final cost function in (4.25) above.

The derivatives with respect to the parameters are;

$$\frac{\delta \ln \bar{C}}{\delta \beta_0^0} = 1, \dots \dots \dots (4.29)$$

$$\frac{\delta \ln \bar{C}}{\delta \beta_1^0} = \frac{-\beta_3^0 q_t}{\beta_1^0 (\beta_1^0 R_t - \beta_2^0 q_t)} + \ln \left( \frac{Z_{t-1}}{q_{t-1}} \right), \dots \dots \dots (4.30)$$

$$\frac{\delta \ln \bar{C}}{\delta \beta_2^0} = \frac{q_t}{\beta_1^0 R_t - \beta_2^0 q_t} + \ln R_{t-1} \dots \dots \dots (4.31)$$

$$\frac{\delta \ln \bar{C}}{\delta \beta_3^0} = \ln inct_{t-1} \dots \dots \dots (4.32)$$

$$\frac{\delta \ln \bar{C}}{\delta \beta_4^0} = \ln \text{roy}_{t-1} \dots \dots \dots (4.33)$$

Substituting (4.29), (4.30), (4.31), (4.32) and (4.33) into Taylor equation (4.28) and rearranging the equation, we obtain the restricted form of indirect final cost function that we estimate,

$$\begin{aligned} \ln \bar{C}_t - \ln \left[ \frac{\beta_1 q_t R_t (1+r)}{q_{t-1} (\beta_1 R_t - \beta_2 q_t)} \right] = & \beta_0 + \beta_1 \left[ \frac{-\beta_2^0 q_t}{\beta_1^0 (\beta_1^0 R_t - \beta_2^0 q_t)} + \ln \left( \frac{z_{t-1}}{q_{t-1}} \right) \right] + \\ & \beta_2 \left[ \frac{q_t}{\beta_1^0 R_t - \beta_2^0 q_t} + \ln R_{t-1} \right] + \beta_3 \ln \text{inct}_{t-1} + \beta_4 \ln \text{roy}_{t-1} + \varepsilon_{t-1} \end{aligned}$$

.....(4.34)

The above model is linear in  $\beta_k$ ,  $k=0, \dots, 4$ , and therefore linear estimation technique can be used to estimate the equation. The starting values of  $k$ , would be the parameter estimates of unrestricted indirect cost model estimated in equation (4.17) (4.18) and (4.19).

The indirect cost functions Unrestricted (FCU), restricted (FCR) and Average cost (FCA) models are employed in testing the theory together with parameters of dynamic optimality condition as presented in equation (4.34) above over range of discount rates to test for Hotelling's principle.

To reject or fail to reject the Hotelling's model is dependent on the kind of data used in the study. Our null hypothesis explains that, Hotelling's framework is empirically not relevant given data used, against the alternative that Hotelling's framework holds and the theory is empirically valid given the data used in the study.

If the probability value of Hausman statistics is less than critical value at 0.05 significance level, then the dynamic optimality condition implied in equation (4.13) is satisfied by our

parameter estimates of indirect final cost models. This also means the restriction (4.13) together with a range of discount rate allows us not to reject Hotelling principle, therefore our data used are consistent with the theory. If the probability value of Hausman statistics is greater than critical value at 0.05 significance level then it indicates the implied dynamic condition restriction is not satisfied by our parameter estimates of indirect final costs equations. And therefore our data are not consistent with the Hotelling's rule predictions.

We reject the model when the data used in the study do not conform to Hotelling's rule predictions and dynamic optimality condition. This implies that the firms are operating at sub-optimal level.

Literature suggests that the theory is still valid in the economics of exhaustible resource even when we reject the Hotelling's framework (Livernois, 2009). However, when we reject the null hypothesis, it indicates that we failed to reject the Hotelling's dynamic condition, and therefore the data included in this study conforms to the Hotelling's framework. Implying that the firms under consideration are operating at optimal level as predicted by theory of exhaustible resources.

### **Objective 3.**

#### **4.3 Simulation and Optimization process using Excel Solver spreadsheet.**

In line with the third objective of determining the optimal extraction path for natural gas, we employ linear programming approach to extract the objective function as extraction cost problem and constraints that are used in the optimization process. The study aims at determining the least cost of extraction. The natural gas optimization process is simulated using excel solver spreadsheet to show the dynamic and optimal paths of gas extraction for the two separate fields of natural gas in Tanzania. The simulation using Excel Spreadsheet

Solver to obtain optimal extraction path is important for three reasons. The first is that it serves as a link from the theory and general models to the real world resource allocation problems. Secondly, optimization for non-renewable resources describes the best allocation as well as level of resource harvest/extraction overtime. Lastly, optimization is useful for policy maker's decisions regarding conservation or further extraction of the resource depending on social welfare and sustainability issues.

#### 4.3.1 The Empirical Model

This study covers optimization of natural gas extraction in Tanzania, and an Excel Spreadsheet solver is used to run the optimization problem. The optimization process to obtain the optimal path is done independently for the two separate fields; SongoSongo and Mnazi bay respectively. Specifically, our objective is to minimize the extraction costs subject to gross extraction levels and the remaining reserves.

The optimal schedule of extraction costs seeks to minimize the total cost of gas extraction. The first term in equation (4.35) represents the cost of quantities extracted and the second term represents cost of reserves, multiplied by discount factor over the period of 60 months of production such as from 2010-2014.

$$\text{Minimize} \quad \sum_{t=0}^T \rho^t \{ \sum_{i=1}^I \ln Cq_t^2 + \sum_{i=1}^I \ln Cr_t \} \dots\dots\dots (4.35)$$

Subject to the following constraints;

$$\sum_{t=0}^{T-1} \ln q_t \geq 0 \quad \dots\dots\dots (4.36)$$

$$r_t = \ln \bar{R} - \sum_{t=0}^T \ln q_t = 0 \quad \dots\dots\dots (4.37)$$

And 
$$\rho^t = 1/(1 + \delta)^t \quad \dots\dots\dots (4.38)$$

$T = 60$  periods (monthly)

Where:  $\delta$  is the discount rate equated by market interest rate of 8% at the period of 2010-2014,  $\rho^t$  is the discounting factor,  $qt$  is the gross gas quantities,  $R_t$  is the remaining reserves and  $C$  is the individual firm extraction costs. Equation (4.36) is a constraint describing the quantities of gas extracted which is increasing over time, and hence the constraint is non-negative. Equation (4.37) shows the field remaining reserves. The reserves are decreasing with increasing extraction overtime and it's also non-negative constraint. We implement our model using solver optimization tool. However, on the current analysis, the model does not include other factors that have effects on costs such as royalties and corporate taxes. The discount rate of 8% is chosen to perform simulation to obtain optimization path. The sensitivity analysis is performed for two point's difference in discount rate such as 6% as lower than and 10% higher than initial discount rate of 8%. The sensitivity analysis for other rates of discount rate levels mentioned will help us to show the time preference and how optimal path would change. The optimization model provides the basis for evaluating the extraction profiles that would be adopted by firms.

#### **4.4 Diagnostic Tests**

This study carries out different tests to determine the appropriateness of the variables and models during the analysis. Diagnostic tests also consider robustness, precision and reliability of our estimated results.

##### **4.4.1 Unit- root Test**

Primarily, a panel unit root test is conducted to test if the variables estimated are stationary or non-stationary for the panel data set used. The unit root test is crucial to avoid the problem of spurious regression due to time series process. Unit root test also helps to

determine the degree of differencing that is needed to achieve stationary before carrying out the dynamic panel data estimation (Greene, 2012).

The Augmented Dickey- Fuller (ADF) test is conducted on all variables used for panel estimation. Extensively, for the matter of robustness check, we also conduct the Im-Pesaran-Shin (IPS) test for unit root test in panel to verify results of the fisher type (ADF) test. The test is conducted on the null hypothesis that each individual unit in the panel has integrated times series indicating all panel variables are non-stationary; the alternative hypothesis is that all panel series are stationary. The conventional probability value of 0.05 is going to be compared with the calculated p-value for every test conducted to determine the stationary or otherwise and their levels for every panel variable.

#### 4.4.2 Hausman Specification test

Hausman (1978) proposed a specification test which underlies the difference between fixed and random effects estimators. Under the null hypothesis that the unobserved individual effects  $\alpha_i$  are distributed independently of regressors  $X_j$ . Hausman test hypothesis is asymptotically chi – squared distributed with k degrees of freedom. The Hausman test is that fixed effects (FE) will be the preferred model if the errors are correlated with the regressors but the null hypotheses does not. This is to say, under null hypothesis random effect (RE) model will be chosen and alternative hypothesis is the fixed effects choice.

It can be written as

$$W = [\hat{\beta}_{FE} - \hat{\beta}_{RE}]' [Var(\hat{\beta}_{FE}) - Var(\hat{\beta}_{RE})]^{-1} [\hat{\beta}_{FE} - \hat{\beta}_{RE}] \quad (4.39)$$

This test is based on the assumption of zero conditional mean. The hypothesis is that the fixed effects model is appropriate and preferred when Hausman test statistics (Prob > Chi<sup>2</sup> = 0.0000) is less than 0.05. Hence we reject the null hypothesis in favour of alternative for

which fixed effects will be ideal model. A fixed effect model examines group differences in intercepts, assuming the same slopes and constant variance across entities.

Similarly, to perform the test of the theory of exhaustible resources, “ Hotelling rule” the Hausman test is required. The test statistics needs an asymptotically efficient estimator under null hypothesis which is not consistent under alternative hypothesis. And secondly, under null hypothesis it needs another estimator that is asymptotically less efficient than the first one and consistent under alternative. Then it is expected that the estimation of equation (4.12) and (4.5) would provide consistent estimates of the parameters of indirect final costs FCU, FCR and FCA regardless of whether the shadow price path conforms to equation (4.10). Then under null hypothesis, the estimation of constrained equations of (4.12) and (4.10) that gives consistent and asymptotically efficient estimates of the coefficients for each indirect cost functions which are FCU, FCR and FCA. Under alternative hypothesis the estimated coefficients for each cost function are inconsistent.

#### **4.5 The Data, Study area and Measurement of variables**

This study makes use of a panel data set. The data is secondary, collected on monthly basis for two firms extracting natural gas in Tanzania over the period of five years from 2010 to 2014. The firms are Maurel and Prom Limited and Songas/Pan-African Energy Tanzania operating in Mnazi bay and SongoSongo Island respectively. Therefore the data span for 60 months, which makes the total of 120 observations given the two firms under study. Other source of data like natural gas gross production and final production for each firm are compiled from Tanzania Petroleum Development Corporation (TPDC) and data on royalties and corporate taxes were obtained from firms and companies’ Web based publications. Two firms are chosen because of data availability.

#### **4.5.1 Method of analysis.**

Statistical package STATA 12.0 is used for the estimation of the specified econometric models and MICROSOFT EXCEL SPREADSHEET SOLVER version 2013 is used to obtain the optimization path.

#### **4.5.2 Definition and Measurement of Variables.**

The following is the description of the variables used to estimate the functions.

*Extraction costs* ( $C_t$ ) is the natural gas extracting costs and is also a dependent variable in this study. This variable is obtained by summing up the sub-cost components that relate to cost of gas production for every month from 2010 to 2014. The costs of production differ across months in a year. A firm can have an increasing or falling gas extraction cost because of type of chemicals and other substances used to pump before refining the products. The costs depend upon physical and chemical characteristics of reservoirs as well as the nature of rocks.

At firm level, it involves higher costs to install the equipments and machines when drilling deeper gas wells, but it is believed that if the natural gas is extracted from deeper depth, the cost of extraction becomes lower when the natural pressure of well is higher. Compared to shallow wells drilled, sometimes the deeper wells have potential of having natural pressure. The natural pressure can pump gas on its own without additional cost and time to employ the artificial lift that will inject pressure to the wells for the natural gas production. This is because on deeper gas wells, the Earth's temperature and pressures are huge and immense (Balthrop (2012) and Andersen *et al* (2009)). Sometimes the extraction cost falls if a firm owns the gas wells of this nature. Therefore extraction costs depends on several

factors which have numerous effects on firm's cost, production and profit functions simultaneously.

*Gross production ( $q$ )*, is the gross quantities of natural gas extracted by a firm. This is the amount of natural gas produced from every operating well in the field on monthly basis. A firm produces millions of metric standard cubic feet (*mmscf*) of gas monthly depending on its production rate. A firm can decide to process it to final production or store it before further processing. The cost can increase or fall depending on the amount of reserves that a reservoir has as well as the natural pressure that a gas well has. The expected sign for this variable will be negative as it depends to the stock of reserves that a firm occupies and production levels.

*Final production ( $z$ )*, is the final refined quantities of natural gas. This is the amount of gas that is further processed, such that all impurities have been removed and gas is ready for transportation via the pipeline to various users for their consumption. The final production of gas also depends on the capacity and rate of gross production, since the final production cannot exceed the amount of gross production quantities produced within a certain period of time. As additional unit of gas is further processed, it involves additional costs to the firm for cleaning up and removing impurities such as air in terms of carbon, nitrogen and water.

Final production of natural gas impact cost function negatively or positively depending the scale of production for that particular firm, as well as the physical and chemical contents of the gas itself when is subject for processing. Hence when a firm is extracting gas and refining it on large scale, then the cost will be lower in aggregate terms compared to small scale refinement. This is because a firm needs to buy chemicals and other inputs for

refining. Therefore if it is operating in large scale the cost is lowered for each additional unit which goes for refinement.

The values for gross production and final production have been converted into standard unit of *million metric standard cubic feet (mmscf)*.

*Remaining reserves R*, is the value of natural gas remaining stock at the field. Given the technological level of the firm, the cumulative and remaining reserves are expected to reduce the costs of extraction to the firm. The fact that reserve deposits may differ in many fields (Sweeney, 1992), as the firm extracts more and more stock of reserves from the ground the cost is reducing or increasing. This depends on the geological formation and the natural pressure of the well to flare gas to the surface before being processed (Pindyck 1978).

To obtain the values of remaining reserves for each month under period of our study, we took each firm proven reserve that were recorded initially before commercial production commences, and deduct the proven reserves with gross natural gas output to obtain the value of remaining reserves. Songo Songo field proven reserves was 385 *Billion Cubic Feet (bfc)* equal to 385,000 *million metric standard cubic feet (mmscf)* in 2009. To get the remaining reserves for the period under consideration, 2010 to 2014, we use the value of 385,000 mmscf and deduct it from field natural gas gross production to obtain remaining reserves for each month. Similarly, for Mnazi bay field, proven reserves was 332 (*bfc*) equal to 332,000(*mmscf*) in 2007. The preceding extracted gross quantities were subtracted to obtain the remaining reserves for each month from 2010 to 2014. Therefore remaining reserves are expected to increase the costs to the firms in long run and hence this variable is expected to be negative.

*Taxes (inct)* are income taxes. The government's imposition of income taxes to gas industry may increase the cost function of the firm. Mintz and Duanjie (2012) explains that forms of taxes like corporate tax or severance tax which directly relate to the production of the resource might have negative impact on the cost behavior of the firm and therefore negative sign is expected. Income tax helps the government to capture a share of the resource rents from the natural gas projects (Sunley, et al 2003). The unit of measurement for this variable is million USD (\$).

*Royalties (roy)* are the royalty charged by government. Royalties are an agreed amount that the firm pays to the resource owner. This is one of the government fiscal policy instruments to obtain share of revenue from its natural resources owned. Royalties influence the cost of extraction since a resource owner has to get an appropriate share of the economic rent generated by the firm resource production. According to Sunley *et al* (2003), when government raises the royalty's levels, the marginal extraction cost of extracting a resource also rises. Thus, higher levels of royalty can limit further investments in the gas industry. This may lead to abandonment of ready productive reservoirs and can also deter the expansion and development of natural gas reserves.

#### **4.6 Summary of the chapter**

The chapter presented the methodology adopted and used in this study. Secondary data were collected from firms and TPDC. Panel data analysis was employed to estimate the cost of natural gas. Restricted cost function was used in estimating the shadow price of the resource. Hotelling's dynamic condition was presented in econometric form and tested using Hausman specification test, in order to test the relevance of the theory. Moreover, to

obtain the optimal extraction path of resource, the optimization process was undertaken by employing linear programming framework using Excel Spreadsheet Solver. Diagnostic test was conducted to ascertain the precision of the results and sensitivity analysis was conducted for robustness check and for the comparison of the results.

## CHAPTER FIVE

### ANALYSIS AND INTERPRETATIONS OF THE RESULTS

#### 5.0 Introduction

This chapter provides analysis and results of the model estimations according to the methodology adopted in the previous chapter. Section 5.1 gives descriptive statistics and the results from unit root test. Section 5.2 provides results on the estimated extraction costs model using Feasible Generalized Least Square (FGLS) and results for robustness check. Section 5.3 presents the results on empirical test of Hotelling's dynamic condition model and facilitates comparative analysis with other literature in this area of study. Section 5.4 describes the results on simulation and optimization path. Finally, section 5.6 presents the summary of the chapter.

#### 5.1 Descriptive Analysis and Unit root test

##### 5.1.1 Data Description

Panel data-set of six variables for two natural gas producing firms are used for analysis. The data is on monthly basis over the period 2010-2014. The choice of firms and time period included in the study is based solely on data availability.

The dependent variable in the study is natural gas extraction costs measured in US dollars (\$). The explanatory variables are gross natural gas output ( $q$ ), final refined natural gas quantities for consumption ( $z$ ) and field natural gas remaining reserves ( $R$ ), all measured in million metric standard cubic feet (mmscf). Other explanatory variables are corporate taxes ( $ctaxes$ ) and royalties ( $roy$ ), measured in US dollars (\$) which captures government share of profit as a resource owner.

### 5.1.2 Descriptive Statistics

Summary statistics of the panel dataset over the period 2010-2014 is presented in Table 5.1 below. The summary statistics include mean, standard deviation, minimum and maximum values as presented below.

**Table 5.1 Summary Statistics of Panel dataset for natural gas extracting firms**

<b>Variable</b>	<b>Observations</b>	<b>Mean</b>	<b>Std.Dev</b>	<b>Min</b>	<b>Max</b>
Firm	2				
Years	5				
Extraction costs <sup>a</sup>	120	445919.5	281560.7	5337.61	2059178
Gross output <sup>b</sup>	120	1386.49	1356.79	27.14	3183.5
Refined quantities <sup>b</sup>	120	1379.14	1351.823	25.96	3170.13
Remaining reserves <sup>b</sup>	120	301494.1	34761.93	221955.8	382822.7
Corporate taxes <sup>a</sup>	120	465420.6	549244.8	719.08	1377500
Royalties <sup>a</sup>	120	273033.8	375364.7	17800.26	1119083

a = measured in US dollars (\$), b= measured in mmscf.

Source: Author's computations

Table 5.1 shows the average cost of extracting natural is about 445,919.5 USD with a maximum cost of 2,059,178 USD for both firms. We also observe the remaining reserves in place are higher for two firms with range of 221955.8 mmscf and 382822.7 mmscf for minimum and the maximum values respectively. Remaining reserves are seen to be higher over the period of study because some of the proven gas reservoirs are not currently under operations. The accomplishment of 36' inch pipeline is expected to boost extraction from proven reservoirs and raise production levels so as to meet demand for domestic, industrial needs and for power generation in the country.

### 5.1.3 Unit- Root Test Results

Basically, before we perform empirical estimation, we need to carry out a unit root test to know whether our variable of interests in our study contains panel unit roots problem or otherwise. We perform a fisher type test which is Augmented Dickey fuller (ADF) Test. For robustness check of ADF results, we also conduct Im- Pesaran- Shin (IPS) panel unit root test. Both tests have a null hypothesis that, all panels contain unit roots. The ADF alternative hypothesis states that, at least one panel is stationary, while IPS test alternative hypothesis explains, some panels are stationary. Tables 5.2 and 5.3 presents the results of ADF and IPS tests respectively. The calculated probability value is compared with critical value at 0.05 significance level. If the calculated probability value on the tables below is less than critical value of 0.05, then we reject the null hypothesis in favor of alternative hypothesis. The ADF test results from table 5.2 suggests, for two variables which are extraction costs and royalties, we reject the null hypothesis that they are not stationary, and therefore at least one panel variable appeared to be stationary at level. The remaining explanatory variables contains unit roots problem at level. Hence, we fail to reject the null hypothesis in ADF test since the calculated p-value is greater than conventional significant level at 0.05. In order to make them stationary, we conduct first difference process. The remaining four explanatory variables which are gross output, refined quantities, and corporate taxes and natural gas remaining reserves appeared to be stationary after first differencing. Their calculated probability values are less than conventional significance level of 0.05. At this juncture, we reject the null hypothesis of unit root problem, hence at least one panels is stationary according to ADF test hypothesis.

**Table 5.2 Augmented Dickey- Fuller test Results**

Variable	Statistic		Probability value
	Stationary at	Value	
Extraction costs	Level	13.7686	0.0000
Gross output	First difference	21.9608	0.0000
Refined quantities	First difference	22.0678	0.0000
Remaining reserves	First difference	2.7483	0.0003
Corporate taxes	First difference	20.5669	0.0000
Royalties	Level	4.9464	0.0000

Note: The statistical values are based on the modified inverse chi-squared (Pm)

**Table 5.3 Im-Pesaran-Shin (IPS) Unit Root Test Results**

Variable	Statistic		Probability value
	Stationary at	Value	
Extraction costs	level	-5.8828	0.0000
Gross output	First difference	-7.9347	0.0000
Refined quantities	First difference	-7.959	0.0000
Remaining reserves	First difference	-7.923	0.0000
Corporate taxes	First difference	-7.5777	0.0000
Royalties	level	-5.9881	0.0000

Source: Author's computation.

For robustness check of our results from ADF test, we carry out Im-Pesaran-Shin (IPS) test. The test results for IPS test are presented in Table 5.3. The IPS test results confirms with the ones obtained under ADF test. For the dependent variable which is Extraction costs and one explanatory variable, royalties, we reject the null hypothesis at 0.05 significance level and therefore at least one panel is stationary at level. Similarly, IPS test shows other explanatory variables become stationary after first differencing. Hence, we reject the null hypothesis of unit root problem, and thus according to IPS test at least some panels are stationary after first differencing.

At this point, our panel data-set can be said to be stationary at such levels mentioned in both ADF and IPS tests and therefore it's free from unit root problem under time series processes.

## **5.2 Model Estimation Results**

To achieve the first objective of determining natural gas extraction costs, we conduct Feasible Generalized Least Square models (FGLS) for our panel data-set. Furthermore, to check for robustness of our FGLS results, we perform fixed and random effects models thereafter.

### **5.2.1 Feasible Generalized Least Square Estimation Results**

The regression is conducted using FGLS for all indirect costs functions which include Unrestricted (FCU), Restricted (FCR), Average Cost (FCA) and Gross costs (GC) function. The results obtained are shown on Table 5.4 below.

Table 5.4 Feasible Generalized Least Square Estimation (FGLS) Results

Type of cost Function	(Unrestricted)	(Restricted)	(Average cost)	(Gross cost)
	$\beta_q = -\beta_z$	$\ln C - \ln z$	$\ln z=0$	
VARIABLES	FCU	FCR	FCA	GC
Gross output, q	-1.097 (2.759)	-5.567** (2.560)	0.959* (0.551)	0.0363 (0.551)
Refined quantities, z	1.138 (2.716)	0.0389 (0.533)		
Remaining reserves, R	-167.4** (45.65)	-147.9** (45.47)	-167.3** (45.58)	-166.4** (45.62)
Corporate taxes (corpt)	-0.00154 (0.122)	-0.0145 (0.118)	-0.0004 (0.120)	0.00805 (0.120)
Royalties (roy)	-0.539*** (0.175)	-0.548*** (0.172)	-0.538* (0.175)	-0.536*** (0.175)
$\alpha_{2011}$	0.605*** (0.198)	0.675*** (0.197)	0.605*** (0.198)	0.600*** (0.198)
$\alpha_{2012}$	0.536*** (0.193)	0.597*** (0.191)	0.536*** (0.203)	0.529*** (0.192)
$\alpha_{2013}$	0.957*** (0.285)	1.041*** (0.282)	0.956*** (0.285)	0.954*** (0.285)
$\alpha_{2014}$	0.986*** (0.240)	1.086*** (0.239)	0.986*** (0.239)	0.985*** (0.240)
Constant	17.70*** (1.698)	17.97*** (1.669)	17.67*** (1.698)	17.67*** (1.698)
Log- Likelihood	-91.7721	-89.5334	-91.7734	-91.8598
Observations	118	118	118	118
Number of firm	2	2	2	2

Standard errors in parentheses  
 \*\*\* p<0.01, \*\* p<0.05, \* p<0.1

Source: Author's computation.

The results of the FGLS model presented in Table 5.4 shows gross output of natural gas has a negative sign for the two indirect costs functions which are unrestricted indirect cost function, *FCU* and restricted, *FCR*. A positive sign which is against the theoretical expectation is seen for the other restricted models which are average *FCA* and Gross cost, *GC* function. Despite the fact that the restricted *FCR* and average cost *FCA* models have different signs for natural gas gross output, they are significant at 5% and at 10% levels in both models. For *FCU* and *FCR*, natural gas gross output coefficient -1.097 and -5.567 implies that a 10% proportionate increase in gross output of natural gas will lead to about 10.97% and 55.67% decrease in marginal cost of gas extraction respectively. Our estimates imply there is inverse relationship between gross output and marginal cost of extraction.

Therefore, as it stands in both theoretical and empirical views, there is negative relationship between marginal cost of extraction and gross amount produced for *FCU* and *FCR* cost models.

The results confirms the earlier findings by Chermak and Patrick (2001,2002, 2009) and Halvorsen and Smith (1991) whose studies suggests that as resource depletes, the marginal costs of extraction decreases. However, each additional unit extracted increases the cost of extraction (U-shaped marginal cost curve) in the long run. As extraction increases, marginal cost declines, reaches a minimum value, then rises again.

Refined quantities parameter ( $z$ ) enters *FCU* and *FCR* with its expected positive sign though the parameter is not statistically significant at traditional levels mentioned above. It implies that a 10% proportionate increase in refined product as result of gross production will lead to about 11.38% and 0.39% increase in marginal processing costs for *FCU* and *FCR*. Similarly, our results for refined quantities supports the findings of (Chermak and

Patrick, 2001) for the restricted cost function estimated. They suggested that the cost of a refined quantity is a necessary component in estimating real costs of extraction. Commonly, it is because natural gas needs further processing such as removal of water and other gaseous components as well as refinement from its extracted gross product before its final consumption.

The parameter estimates of remaining reserves enter the model significantly at 1% and 5% significance levels and coefficient is negative for all four estimated regression models. Our result indicates there is significant negative relationship between stock of remaining reserves and resource extraction costs. This means the extraction costs are inversely related to stock of remaining reserves. Studies done by Pindyck (1978), Lin and Zhang (2011) also explains the observed inverse relationship between stock of remaining reserves and marginal extraction costs.

There are several reasons for the observed inverse relationship between the variables. Among the reasons are variations in geological formation of the field, differences in reservoirs natural pressure to flare gas to the surface and differences in production costs to bring gas to the surface. When production matures and the resource is depleted from the field, the well's natural pressure reduces and firm would incur more costs of extraction from each unit of reserves extracted. This is because a firm needs artificial lifts to bring the gas to the surface (David and Cairns, 1999) which involves extra cost.

Furthermore, the reason for the inverse relationship between reserves and extraction cost might be attributed to some operating reservoirs that are getting older. The fields started commercial production in 2004 and the other in 2007 in the country. Therefore these

reservoirs might have the possibility of adding costs of extractions to the firms since fields are aged and suffer from reduced natural pressure to bring gas to the surface.

### **Taxes and Royalties**

Our estimated results from Table 5.4 found corporate taxes estimate is insignificant but it is inversely related with natural gas marginal extraction cost. In Tanzania, corporate taxes are charged at 30% of company's profit. However, royalties is negative as expected and is significant at 1% for FCU, FCR and GC and at 10% significance level for FCA. Study results shows royalty rate affects gas extracting cost. The rate of royalty for natural gas firms in Tanzania is fixed at constant rate of 12.5 % for onshore and 7.5% for offshore natural gas production.

The study shows that, current rates of royalty and corporate taxes seem to have negative effects on the cost of extraction. But it is difficult to assess if 30% corporate tax is optimal for government or not. This is because a corporate tax of 30% is paid on annual basis and it is applicable for all corporate companies in the country. At this juncture, it is beyond the scope of this study to determine optimal rates of corporate taxes and royalties in the country. However, a corporate tax is not specific to extractive sector compared to royalty tax. Natural gas sector in the country is still at infancy stage, therefore charging higher taxes to gas extracting firms would have negative implications to investments and development of the sector since there are other types of taxes and charges beyond corporate taxes that are paid overtime. Furthermore, our study argues that determining optimal taxes does not mean charging higher tax to oil and gas companies. But policy makers need to look at a tax that will ensure government and companies' objectives [Smith (2012) and Tilton (2004)].

Royalty rate on resource extraction is significant as it acts as payment to the government for the right to use natural resource as a factor of production and it is also a contractual obligation to exploit resources over limited period of time (Conrad, Hool and Nekipelov, 2009). The institutional settings and design of royalty must ensure government maximizes its cash flow from the right to exploit the resource. Royalty should be designed to persuade optimal resource extraction paths, capture economic rents and ensure government flow of revenue without distorting firm's choices on investment and shutdown periods. For royalty rate to be optimal, (Boadway and Keen, 2014) government should design time consistent royalty scheme that will ensure appropriate time path of the resource to cover initial investment as well as extraction costs. In addition, the rate should be conditional to resource stock at initial period. If the rate is constant for long time periods, firms will be induced to extract slowly as long as royalty is positive and thus influence firm's early shutdown since the production cost is higher. When a firm faces higher production cost, it has an incentive to deplete resource quickly which may lead to resource inefficiencies and reduction of government proceeds in the long term.

The study argues for favorable tax policies that will induce more FDI inflows and private investments to the sector. A challenge in practice is to know the effects to the economy when rising or lowering taxes and royalty levels to extractive firms. This is because any shift of tax policy will have effect on the net stream of income to investors and government revenues. For that reason, to determine the optimum rate for corporate taxes and royalties, institutions should assess the existing fiscal regime and examine if the behavior of gas firms change on their extraction profile when the tax and royalty rates are set towards optimum rate.

Our results obtained above should be viewed as applying to short run period because it is limited to only five year period due to data limitations. However, it is anticipated that, when all 23 natural gas extracting firms converge to commercialization of gas production, (including the ones under development stages now) from 2020, then the differences we have observed in this study would change in the long term considering firms behaviors, structure and market operations in the economy.

### **5.2.2 Robustness Check of Estimation Results**

To check for robustness of our FGLS estimation results above, we also perform random (RE) or fixed effects (FE) estimations which were subject to the output results of Hausman specification test. The results of Random (RE) models are presented in the Appendix 1. It is worth-noting that our FGLS results shown in Table 5.4 do not have substantial differences with the estimation results obtained under RE model in (Appendix 1) in-terms of the signs and significance of the parameter estimates. Though we have observed that there is no difference between the two estimation techniques used, our study supports the use of panel FGLS results. The results are far better than RE estimates because FGLS appears to be a better technique when a model suffers from the presence of heteroskedasticity and autocorrelation. Thus, this argument justifies the choice of FGLS over RE in our study to explain how quantities of gas extracted, remaining reserves, corporate income and royalties' determine cost of natural gas extraction in Tanzania.

### **Estimating Shadow price**

The estimated shadow price is different from actual resource price of natural gas, but is one of the essential component that should be included in the price formation for natural gas. Using the formula presented in equation (24) page (65) together with Lemma 1 ( $\mathbf{m} = -\bar{C}_q$ )

and estimated restricted cost function (FCR) ,we further calculate the shadow price of natural gas in Tanzania. We found the average shadow price of \$ 6.33 per million BTU, minimum of \$ 0.42 per million BTU and a maximum price of \$ 10.46 per million BTU respectively. A BTU (British Thermal Unit) is the amount of heat necessary to raise one pound of water by 1 degree Farenheit (F) (Hofstrand, 2008). For many domestic and international markets for natural gas, the selling price is always measured in USD per million BTU. The selling price of natural gas highly depends on the heating value of the gas measured in million metric British thermal Units (mmBtu).

The shadow price presents the rate of appreciation or opportunity cost of resource extraction that would ensure optimal depletion rates. The study argues that, the average estimated shadow price presented the rate of appreciation of the resource but it is un-able to un-cover some peculiar characteristics, for both firms and fields due to data aggregation. Some essential characteristics like age of each producing well, reservoir properties and location are important in explaining resource scarcity in-terms of shadow price but can be hidden due to data aggregation (Chermak and Patrick, 2002).

Hotelling's rule predicts an increasing trend of the nonrenewable resources prices with a declining production rate. But the studies conducted with the available data, found that the prices have remained more or less constant in real terms despite increasing extraction rates for some time. Empirical studies argue that, not only will shadow price provide the highest proportional share to the natural gas price (Hart and Spiro, 2011). It is imperative to note that other components like proportion of taxes, technological advancements and global natural gas market have a significant role in natural gas price formation. These factors have

potential effects in determining gas prices that will serve domestic and international gas markets.

Our study further compares estimated average shadow price of \$ 6.33 per million BTU to domestic actual selling price of natural gas in Tanzania. The domestic price ranges between \$ 6 and \$ 12 per million BTU. We found that, average shadow price accounts for almost equivalent minimum range of current range of gas price in the country.

Moreover, the study conduct sensitivity analysis by assessing the prediction of increasing resource prices, by comparing our estimated average shadow price with the real world actual natural gas prices over our study period 2010-2014. The data for comparison were compiled from among three key gas markets in the world. These includes Henry hub gas market in United states(US), European Gas market (UK) and Japan LNG market which serves mostly Asian countries (see appendix 2). The world actual market prices at Henry Hub United States gas market range from \$ 4.4 in 2010 and a price of \$ 14 per million BTU in 2014 with average price of \$ 3.8 per million BTU. European (UK) gas market has an average price of \$ 10.11 per million BTU over the period. And lastly, in 2014 the actual market price at Japan LNG market was \$ 11 per million BTU with average price of \$ 14.15 per million BTU. The reason behind this comparison with our estimated shadow price is that, it is interesting to know if our estimated shadow price resembles the actual values and trends of natural gas prices in the world. In addition to that, comparison of our estimated shadow price of \$ 6.33 per million BTU with domestic and international gas prices is useful to the institutions and policy makers to look on how the component of scarcity of resource “shadow price” can be included in designing or fixing current and future gas prices at domestic market as well trading outside the region.

From sensitivity analysis, we observe that, our average shadow price is lower compared to actual European gas market price that records the average of \$ 10.11 per million BTU over 2010-2014 periods. This means that, the observed shadow price in Tanzania is closer to current domestic market price but it is lower compared to actual global gas price on average, considering European gas market and Japan LNG gas market prices. Therefore, the study reveals that at some point the element of resource appreciation which is shadow price has not been included in the formation of natural gas price in the country.

There are still discussions in the literature as to what extent the actual observed resource price might include the crucial component of resource appreciation overtime. Although the shadow price explains how scarce the resource is, but it should not be the only component used as the basis in designing important sectorial policy and shaping or influencing real natural gas market prices. This is because, sometimes resource markets fail to assign values to the natural resource in the ground according to Hotelling's theory. This was also argued by (Hart and Spiro, 2011). There can be several factors explaining this observed pattern. One, in theory, the observed natural gas price trends can be as a result of dynamic costs structures within firms and uncertainties in production. Other factors might be technical progress and capacity constraints especially for natural gas firms in Tanzania which are still under the infancy stage. Other practical factors which can explain the observed price trend and empirical relevance of Hotelling's model are more or less related to difficulties in obtaining and gathering relevant data that would have long time span to perform shadow price estimations. In addition to that, difficulties associated with data aggregation on various types of nonrenewable from different operating firms pose

limitations in estimating the trend and predicting the prices of nonrenewable resources (Chermak and Patrick, 2007).

## Objective 2.

### 5.3 Empirical Test of Hotelling's Principle

The empirical test of Hotellings theory is carried out using various discount range and cost models. Hausman test results are reported in Table 5.5 below. The test is performed for three indirect cost functions that were restricted with dynamic optimality condition. Hausman test is used to compare the restricted and unrestricted function for each of the cost model with various discount range, lower and higher than 8%, such as from 1% to 20%.

**Table 5.5 Dynamic Optimality Test Results**

<b>Hausman Statistics</b>			
<b>DISCOUNT RATE "<math>\delta</math>"</b>	<b>FCU</b>	<b>FCR</b>	<b>FCA</b>
0.01	6.78	4.79	3.53
0.02	7.08	4.77	3.51
0.05	7.09	4.71	3.45
0.06	7.09	4.71	3.43
0.08	7.10	4.70	3.39
0.1	7.11	4.62	3.35
0.15	7.12	4.52	3.26
0.2	7.13	6.96	3.18

Source: Author's computation

Table 5.5 presents output of Hausman test statistics for all discount rates. The results are chi- square distributed with four degrees of freedom for all cost functions. The critical value of test statistic is 9.488 for 4 degrees of freedom at 0.05 significance level. The test has a null hypothesis that unrestricted cost function is efficient but inconsistent. The

alternative is that constrained cost function is efficient and consistent estimate. The results show the calculated probability value of Hausman statistics are greater than the critical value at 5% level of significance for all models FCU, FCR and FCA respectively. The test results indicate that we fail to reject the null hypothesis implying that unrestricted cost function is efficient but inconsistent. Hence, there is no significant difference between the unrestricted and restricted cost models tested.

Therefore, our results obtained on Table 5.5 suggest that, the dynamic optimality condition does not satisfy parameter estimates for all indirect cost functions together with range of discount rates tested. Thus, we fail to reject the null hypothesis at 0.05 significance level and hence the Hotelling's principle is rejected since our data used is not consistent with the theory predictions. Then it means the behavior of the natural gas firms in the country do not conform to Hotelling's prediction and dynamic optimality condition. Furthermore, the production decisions for these firms are not effectively taking the arrangements of current production and their path is not economically optimal; since their extraction paths are inconsistent with the theory of exhaustible resources. Hence, the study revealed that the firms extracting natural gas in Tanzania are operating at sub-optimal level according to Hotelling's prediction and dynamic optimality condition.

Comparing with other studies, our test results are in sharp contrast with the studies done by Lin (2009), Caputo (2011), Divovich (2011), Slade and Thille (2009). Their test results did not reject the Hotelling's theory for all discount rate tested although they all employed different natural resources and different estimation techniques over time. Interestingly, our test results also differ with results obtained by Chermak and Partrick (2001) where similar test technique is employed. They found natural gas is produced in a manner consistent with

Hotelling's prediction for natural gas extracting firms in Wyoming and Texas in Canada. However, our results are similar to the conclusion made by Young (1992), Halvorsen and Smith (1991) and Hart and Spiro (2011) where natural resource market tested was not consistent with theoretical model of Hotelling's and its prediction. And therefore the observed behaviors of competitive resource extracting firms are operating at sub-optimal level and resource is not produced in manner consistent to the theory of exhaustible resources.

There are many factors attributed to the observed trend of mixed results. These include differences in the estimation techniques, differences in the type of natural resources tested, data span and time of observed data as well as differences in data aggregation. These factors have a significant influence on the Hotelling's test results obtained by several studies to-date.

### **Objective 3**

To achieve objective three of examining the optimal extraction path of gas fields, the study used excel spreadsheet Solver to simulate the optimization path for Songo Songo field and Mnazi bay field using discount rate of 8%. The results of optimal extraction path at 8% discount rates are presented in Table 5.6 for Songo Songo field for the year between 2010 and 2014. Mnazi Bay optimal extraction schedule results at 8% discount rate are presented in Table 5.7. In addition, we replicate our results obtained by simulating the path when lower and higher than 8% discount rates are adopted. The sensitivity analysis results of optimal extraction path at 6% and 10% discount rates are presented at Appendices 3 and 4 when discount rate is at 6% and appendices 5 and 6 when discount rate is at 10% for both natural gas fields respectively.

**Table 5.6 Optimal Extraction Path for Songo Songo Natural Gas Field at 8% Discount Rate**

Discount rate ( $\delta$ )=0.08      Discount factor ( $\rho$ ) = 0.92593								
Initial values before optimization						Optimized values		
Months 2010-2014	Initial total cost	Quantities extracted	Total field reserves	Initial net reserves	Present value net cost	Optimized quantities	Optimized reserves	Optimal cost path
1	12.64	7.69	12.855	12.86	841.93	0.471	12.86	153.06
2	12.85	7.65	12.850	5.17	702.08	0.467	12.38	138.81
3	12.92	7.73	12.844	5.20	665.53	0.449	12.38	129.09
4	12.82	7.64	12.838	5.12	598.00	0.461	12.39	118.81
5	12.92	7.67	12.833	5.20	563.51	0.461	12.38	110.70
6	12.51	7.74	12.826	5.16	513.19	0.468	12.37	99.27
7	12.88	7.85	12.820	5.09	500.78	0.470	12.36	94.51
8	12.87	7.83	12.813	4.97	460.72	0.441	12.35	87.22
9	12.53	7.77	12.806	4.98	409.64	0.481	12.37	79.03
10	12.97	7.86	12.799	5.04	401.46	0.478	12.32	75.40
11	13.20	7.75	12.793	4.94	368.18	0.488	12.32	71.12
12	13.84	7.70	12.787	5.04	353.41	0.433	12.30	68.67
13	12.91	7.69	12.780	5.09	305.20	0.467	12.35	59.68
14	12.75	7.65	12.774	5.09	275.92	0.485	12.31	54.46
15	13.16	7.81	12.767	5.13	273.97	0.431	12.29	51.75
16	12.83	7.72	12.761	4.96	241.91	0.471	12.34	47.01
17	13.26	7.63	12.755	5.04	226.71	0.459	12.29	44.80
18	13.05	7.87	12.747	5.12	219.09	0.484	12.30	40.91
19	13.44	7.97	12.739	4.88	213.07	0.482	12.26	38.91
20	13.69	7.99	12.730	4.77	201.51	0.450	12.26	36.59
21	13.05	7.93	12.722	4.74	175.43	0.451	12.28	32.37
22	12.89	7.98	12.713	4.79	162.25	0.462	12.27	29.60
23	12.65	7.91	12.705	4.74	145.11	0.483	12.25	26.89
24	12.84	8.00	12.696	4.79	139.44	0.497	12.22	25.25
25	13.01	7.95	12.687	4.69	128.95	0.486	12.20	23.62
26	12.87	7.94	12.678	4.74	117.92	0.484	12.20	21.63
27	13.33	8.03	12.669	4.74	115.54	0.444	12.19	20.69
28	12.78	8.01	12.659	4.64	101.85	0.437	12.22	18.40
29	12.78	8.00	12.650	4.65	94.14	0.459	12.22	17.06
30	13.27	8.02	12.640	4.65	90.85	0.452	12.19	16.34
31	13.49	8.05	12.630	4.62	86.22	0.449	12.19	15.37
32	13.35	8.05	12.619	4.58	79.01	0.460	12.18	14.10
33	12.89	8.01	12.609	4.56	69.93	0.520	12.16	12.64
34	14.05	8.07	12.599	4.60	71.50	0.413	12.09	12.59
35	12.40	7.99	12.589	4.53	57.39	0.433	12.19	10.38
36	12.43	8.04	12.578	4.59	53.85	0.447	12.16	9.62
37	13.04	8.03	12.567	4.54	52.24	0.376	12.13	9.28
38	12.72	7.93	12.558	4.53	46.00	0.390	12.19	8.43
39	12.78	8.02	12.547	4.63	43.78	0.388	12.17	7.82
40	12.99	7.95	12.537	4.53	40.53	0.390	12.16	7.36
41	13.03	7.94	12.527	4.58	37.52	0.392	12.15	6.83

42	12.62	7.98	12.516	4.59	34.03	0.443	12.13	6.14
43	12.81	8.02	12.505	4.53	32.23	0.460	12.07	5.75
44	13.14	7.98	12.494	4.48	30.32	0.459	12.05	5.45
45	13.14	7.98	12.483	4.51	28.06	0.452	12.03	5.04
46	12.71	8.02	12.471	4.50	25.36	0.450	12.03	4.51
47	12.54	7.94	12.460	4.45	22.73	0.474	12.02	4.12
48	13.78	8.01	12.449	4.52	23.56	0.448	11.99	4.18
49	13.97	8.01	12.437	4.44	22.05	0.384	12.00	3.91
50	13.01	7.89	12.426	4.43	18.50	0.329	12.05	3.37
51	12.64	7.97	12.414	4.54	17.00	0.332	12.10	3.05
52	13.19	7.79	12.405	4.44	15.68	0.278	12.08	2.93
53	12.76	7.85	12.394	4.62	14.30	0.328	12.13	2.64
54	13.55	7.92	12.383	4.55	14.29	0.258	12.07	2.58
55	12.72	7.97	12.371	4.46	12.53	0.365	12.13	2.26
56	13.58	7.96	12.359	4.41	12.38	0.304	12.01	2.21
57	12.70	7.93	12.347	4.39	10.64	0.491	12.05	1.94
58	12.99	7.90	12.335	4.41	10.01	0.480	11.86	1.81
59	13.96	7.90	12.323	4.43	9.96	0.824	11.85	1.87
60	13.27	7.92	12.310	4.42	8.80	12.310	11.50	21.36
				4.39	<b>10,607.66</b>		0.00	<b>2,031.18</b>

Source: Author's computation

Table 5.6 displays the initial set up and results for an optimal extraction path at discount rate of 8% for Songo Songo natural gas field. Solver allowed one to change the initial values of extraction cost, extracted quantities and stock of reserves by minimizing the sum of present value discounted cost and calculate the optimal solution path for these values to the end of period  $t=60$ . The results show that the present value of discounted sum of cost was \$ 10607.66 before optimization and Solver found the optimal sum of cost \$ 2031.18 over the period of study. Given our specified objective function, the result reveals that our extraction profile fulfilled both constraints. In each period, extracted gas quantities are non-negative and field remaining reserves diminishes over the depletion path, and reserved are constrained to be zero at the end of the optimization period. Furthermore, the simulation path shows that, it is optimal to extract 0.471 mscf units of gas at a cost of \$153.06 for the first period and 0.467 mscf units of gas at a cost of \$ 138.81 for the second period and so on. Songo Songo's field optimal extraction quantities have little variation

along the time path, while the stock of remaining reserves is falling with declining optimal cost path.

It is worth noting that, when we set our initial stock of reserves to deplete up to the final period such as  $t=60$ , the optimal extraction goes slowly and increases towards  $qt^*=12.31$  mscf units as optimized stock of reserves approaches  $rt^*=11.50$  mscf. Furthermore, the optimal cost changes from \$ 1.87 to \$ 21.36 at the last months of optimization when initial reserves are assumed to deplete at the end period  $t=60$ . Therefore we found that, higher levels of stocks will always have an opportunity cost of lower extraction during the initial period, although higher discount rates have an incentive to change extraction schedule to extract more units at shorter periods to maximize firm's benefits.

**Table 5.7 Optimal Extraction Path for Mnazi Bay Natural Gas Field at 8% Discount Rate**

Discount rate ( $\delta$ )=0.08						Discount factor ( $\rho$ )=0.925926		
Initial values before optimization						Optimized values		
Months 2010-2014	Initial total cost	Quantities extracted	Total field reserves	Initial net reserves	Present value net cost	Optimized quantities	Optimized reserves	Optimal cost path
1	11.83	3.36	12.608	12.61	261.46	0.470	12.61	140.55
2	12.06	3.30	12.608	9.25	208.40	0.435	12.14	127.50
3	11.40	3.57	12.608	9.31	199.47	0.484	12.17	112.29
4	11.92	3.54	12.608	9.04	189.13	0.428	12.12	107.83
5	11.14	3.50	12.608	9.07	161.78	0.521	12.18	94.43
6	12.53	3.53	12.608	9.11	170.13	0.327	12.09	96.31
7	8.58	3.36	12.608	9.08	102.05	0.638	12.28	63.54
8	11.91	3.52	12.608	9.25	139.34	0.479	11.97	78.52
9	12.39	3.58	12.608	9.09	135.62	0.458	12.13	76.47
10	12.14	3.99	12.607	9.03	140.21	0.440	12.15	69.38
11	11.75	4.01	12.607	8.62	124.30	0.496	12.17	62.56
12	12.53	3.98	12.607	8.60	121.84	0.434	12.11	61.22
13	11.73	4.00	12.607	8.62	106.29	0.477	12.17	53.47
14	12.27	3.82	12.607	8.60	96.94	0.439	12.13	51.49
15	11.67	3.97	12.606	8.79	90.32	0.476	12.17	45.61
16	12.00	3.91	12.606	8.64	83.94	0.475	12.13	43.29
17	12.32	4.06	12.606	8.69	83.75	0.455	12.13	41.08
18	12.15	4.15	12.606	8.55	78.28	0.467	12.15	37.61
19	12.44	4.07	12.606	8.46	72.14	0.452	12.14	35.58
20	12.37	4.06	12.606	8.53	66.36	0.496	12.15	32.91

21	13.33	4.02	12.605	8.55	65.36	0.438	12.11	32.58
22	12.66	4.08	12.605	8.59	58.71	0.446	12.17	28.80
23	12.17	4.06	12.605	8.53	51.89	0.532	12.16	25.78
24	14.07	3.94	12.605	8.54	53.36	0.403	12.07	27.16
25	12.49	3.96	12.605	8.67	44.37	0.455	12.20	22.62
26	12.56	3.99	12.604	8.65	41.65	0.452	12.15	20.97
27	12.45	4.00	12.604	8.62	38.33	0.483	12.15	19.30
28	12.97	3.95	12.604	8.61	36.45	0.468	12.12	18.56
29	12.95	4.09	12.604	8.65	35.25	0.472	12.14	17.18
30	13.03	3.98	12.604	8.52	31.52	0.475	12.13	16.00
31	13.11	4.03	12.603	8.62	29.96	0.448	12.13	14.88
32	12.65	4.01	12.603	8.58	26.60	0.476	12.16	13.34
33	13.16	4.03	12.603	8.59	25.77	0.452	12.13	12.80
34	13.24	4.09	12.603	8.57	24.46	0.384	12.15	11.89
35	11.84	4.08	12.603	8.51	20.17	0.479	12.22	9.97
36	12.86	4.12	12.603	8.52	20.51	0.428	12.12	9.91
37	12.94	3.92	12.602	8.49	17.88	0.454	12.17	9.29
38	13.09	3.90	12.602	8.69	16.80	0.464	12.15	8.69
39	13.21	4.09	12.602	8.70	16.71	0.443	12.14	8.10
40	12.94	4.10	12.602	8.51	15.07	0.470	12.16	7.37
41	13.05	4.13	12.602	8.50	14.23	0.472	12.13	6.87
42	13.02	4.08	12.601	8.47	12.89	0.479	12.13	6.35
43	13.01	4.09	12.601	8.52	11.99	0.474	12.12	5.87
44	12.86	4.09	12.601	8.51	10.97	0.471	12.13	5.37
45	12.82	4.10	12.601	8.51	10.15	0.468	12.13	4.96
46	12.97	4.17	12.601	8.50	9.74	0.478	12.13	4.65
47	13.54	4.18	12.600	8.43	9.42	0.443	12.12	4.48
48	13.25	4.19	12.600	8.42	8.55	0.433	12.16	4.07
49	13.18	4.13	12.600	8.41	7.74	0.397	12.17	3.74
50	12.70	3.94	12.600	8.47	6.49	0.444	12.20	3.36
51	13.13	4.14	12.600	8.66	6.69	0.415	12.16	3.20
52	13.18	4.10	12.599	8.46	6.09	0.427	12.18	2.98
53	13.19	4.17	12.599	8.50	5.79	0.464	12.17	2.77
54	13.93	4.14	12.599	8.43	5.58	0.405	12.13	2.69
55	12.78	4.19	12.599	8.46	4.83	0.519	12.19	2.31
56	12.97	4.22	12.598	8.40	4.57	0.563	12.08	2.16
57	13.47	4.19	12.598	8.37	4.34	0.550	12.04	2.07
58	12.49	4.28	12.598	8.41	3.85	0.739	12.05	1.81
59	12.70	4.27	12.598	8.31	3.60	0.425	11.86	1.63
60	14.54	4.24	12.597	8.33	3.78	12.597	12.17	24.53
				8.35	<b>3,453.87</b>		0.00	<b>1,862.68</b>

Source: Author's computation

Table 5.7 shows the optimal extraction path for Mnazi bay natural gas field at 8% level of discount. The results found are somehow related from what has been obtained from Songo Songo extraction profile. We ask Solver to optimize the extraction profile by minimizing

the initial discounted sum of present value of cost at \$ 3453.87, the results found the optimal sum of cost at 8% discount rate for Mnazi Bay field is \$ 1862.68. When we set our initial stock of reserves to deplete up to the final period such as  $t=60$ , the optimal extraction is goes slowly and increases towards  $q_t^*=12.60$  mscf units as optimized stock of reserves approaches  $r_t^*= 12.17$  mscf. Also, the optimal cost declined from initial periods and rose to \$ 24.53 on the last month. The unique feature about Mnazi Bay field is that, the quantities extracted at field are lower than the field's capacity to produce. Therefore, we can argue that, Mnazi Bay field optimal extraction cost path declines, however the stock of reserves is still higher even if we have assumed and constrained the stock of reserve to be zero at the end of optimization period such as  $t=60$  months.

At 8 % level of discount rate for both natural gas fields, the results shows the optimal paths of gas extraction are downward sloping, which suggests that firms will have an incentive to extract more and be steady because of higher discount factor.

The sensitivity analysis results for both fields at 6% the results are presented at Appendices 3 and 4 for Songo Songo and Mnazi bay fields respectively. We found the optimal extraction paths rose as discount rate is lowered at for both fields. The sums of optimal cost for both fields are higher than when discount rate of 6% is used. When 6% discount rate is adopted, the results shows the extraction profile is slow and hence the firms and institutions are geared towards the conservation of the resource. In addition, lower extraction profiles can be attributed with other factors such as lower prices at the resource market or falling demand. The gas optimal path at 6% discount rate is downward sloping but it is less steep than when discount rate is 8%.

The results of sensitivity analysis at 10% discount rate are presented at Appendices 5 and 6 for both fields respectively. We found the optimal extraction paths fall as discount rate increased for both fields. The sum of optimal cost at 10% discount level is lower than the previously used discount rates to obtain the optimal paths. The optimal path obtained is also downward sloping but it is steeper than when discount rate was 8%. This is because future costs are discounted more. In conclusion, our optimized extraction paths shows that the optimal cost path decreases as more quantities are extracted at 10% discount rate and hence there is high incentive for firms to extract more quantities of gas and quick. This is because the firms would find it cheaper to extract now, as the cost of extraction is lower. In the long run, quick resource extraction might be considered unsustainable for the country's benefits.

The study has revealed important results about the role of discount rate in simulating and optimizing extraction profiles. As the discount rate increased such as from 8% to 10%, the sum optimized cost is decreasing with falling quantities of extraction. Although higher discount rate reduces the cost of extraction, but it induces more and quick gas depletion. Shorter time preferences of resource extraction may limit sustainable extraction schedule and lower value and the opportunity cost of the resource. Thus, it is unsustainable to extract more units at current period, if the sum of discounted cash flows and proceeds from the natural gas are not invested to capital re-generating activities such as developing human capital, which may ensure society fair share of revenue to the government as well as future benefits to the society.

However, the evolution of price and time path of extraction are highly influenced by other factors such as market structure, information on new available stock of reserves and

technological change to provide the basis for explaining resource price, discounted profits and discounted costs. Nevertheless, it is beyond the scope of the current study and therefore these factors have not been taken into consideration in simulating our extraction paths.

#### **5.4 Summary of the chapter**

This chapter of the study analyses the panel data-set of two natural gas firms to determine extraction cost as well as testing the Hotelling's principle. We compared our dynamic optimality results with other related work in the area of nonrenewable resource extraction. We also presented the results of simulated gas extraction paths. A unit root test was conducted to ascertain the stationarity and non-stationarity of the panel data set. The results by both ADF and IPS confirmed the stationary nature of some of the variables, some were stationary at level and others became stationary after first difference.

In our quest to determine gas extraction cost and testing Hotelling principle, the study analyzed the data set by employing Panel Feasible Generalized Least Square (FGLS) to determine extraction cost. In addition, we estimated shadow price as a result of estimated restricted cost function. Hotelling principle was tested with various discount range following constrained and unconstrained cost functions developed.

The results of the FGLS show that the quantity extracted, stock of remaining reserves and royalties have an inverse relationship with the cost of extracting gas. Furthermore, we checked the robustness of the FGLS model results by using panel RE and FE models. Interestingly, we found that the results confirms with FGLS for all cost functions tested (Appendix 1).

Furthermore, the study estimated the shadow price of the gas and found the minimum price and average price to be \$ 0.41 and \$ 6.33 per million BTU respectively. We further compare the average estimated shadow price with actual domestic and International price of gas. We found the average price to be closer to domestic price of \$ 6 to \$ 12 per million BTU but lower compared to European (UK) international gas market price with average of \$ 8.33 per million BTU.

We perform Hotelling test for the cost function together with Lemma 1 described in chapter four above (page 65) and various discount rates and results suggests the natural gas extraction firms in the country are not producing gas in a manner consistent with theory. Thus, the study argues that gas firms in Tanzania are operating at sub-optimal level according to Hotelling principle.

The optimal extraction path was performed by minimizing sum of extraction cost using excel Solver spreadsheet. We perform the simulation using 8% and replicate our results at 6% and 10% discount rates respectively. We found that the optimal path involves slow but increasing extraction units with declining cost path when discount rate is 8%. The optimal average cost is downward sloping. We also found that the optimal paths of extracting costs decrease when higher discount rate is adopted. This means the future extraction costs are discounted more and firms would find cheaper to extract now, than in future period.

## CHAPTER SIX

### SUMMARY, CONCLUSION AND RECOMMENDATIONS

#### 6.0 Introduction

This chapter provides a summary of the main findings and results of the study. In addition, some recommendations for policy and further research are presented. Section 6.1 offers the summary. Section 6.2 presents the conclusion while section 6.3 gives policy recommendations and areas of further studies. Lastly, section 6.4 discusses the limitations of the study.

#### 6.1 Study Summary

Natural gas extraction as energy resource in Tanzania is important for boosting economic growth and development of the country. A theory of nonrenewable resource has been the focal point in explaining and understanding the behavior of resource markets in the world. Hotelling's theory has been subjected to a lot of empirical test to ascertain its relevance of nonrenewable resources markets in the world. Meanwhile, there are no concrete empirical studies on testing the Hotelling's theory regarding nonrenewable resources such as natural gas in Tanzania. Moreover, empirical studies done on this arena in other countries on different resources, overtime provides conflicting and mixed results on the power of the Hotelling's theory to explain the trend of resource prices and behavior of resource markets that are seen at present. Thus, the rationale behind this study is to test whether the behavior of natural gas firms in Tanzania are consistent with Hotelling theory and its dynamic optimality condition. This study therefore sought to determine natural gas extraction costs, estimate the shadow price, test Hotelling's principle with various discount rates and examine extraction path that optimizes the cost of extracting the resource. The study used

monthly panel data over the period 2010 to 2014 for two natural gas operating firms in the country.

To accomplish the set of objectives, two methods were employed namely, Panel FGLS and linear programming approach. The models were selected to match the theoretical and empirical linkages established to test the theory as well as examine optimal paths.

To estimate natural gas extraction costs, Feasible generalized least square (FGLS) for panel data was adopted. A robustness check of our FGLS results was conducted using panel Random Effects (RE). Both FGLS and RE techniques gave us almost similar results on the signs of parameter estimates. A shadow price which ascertains the rate of appreciation of natural gas resource was also computed after estimating restricted indirect cost function (FCR) and applying its formula.

The parameter estimates of specified cost models were restricted, to be able to test the Hotelling's framework at 8% discount rate and we allowed variations of discount rate 1% to 20% as sensitivity analysis. Using panel data technique, the unrestricted model and restricted model were estimated, and later the Hausman statistics was performed to test the Hotelling's theory. The cost functions were specified as Unrestricted (FCU), restricted (FCR) and average cost (FCA) and used independently to test the theory together with the range of discount rates. Hausman statistics test results were not significant at critical value of 5%. Therefore, our results revealed that the gas operating firms are not producing in a manner consistent with Hotelling's framework and its dynamic optimality condition. The conclusion we made is similar to the work done by Halvorsen and Smith (1991) and Young (1992) that the nonrenewable theory is rejected.

Finally, linear programming approach was adopted to examine natural gas optimal extraction path that will minimize cost of extraction for each natural gas firm in Tanzania. Microsoft excel spreadsheet Solver was used to simulate the optimization paths at 8% discount rate. We found the optimal paths of extraction cost to be reducing with slow increase in the quantity of gas extracted over the study period for both firm. We also found that the optimized cost function declines when it approaches the end time of optimized path. Additionally, we conducted sensitivity analysis with 6% and 10% discount rate for both fields respectively. The optimal cost path was increased with decreasing quantity extracted at 6% discount rate level while the optimal cost path decreased when the discount rate was increased to 10%. This means the fields are depleted quickly when discount rates are higher. Therefore the time path of resource extraction would be shorter.

## **6.2 Conclusion**

The major findings made in this study are that, the firm's extraction costs is inversely related to quantity extracted and the field's remaining reserves over the period of our study, 2010 to 2014. One possible reason for this occurrence could be that the natural pressure of the wells may have been reduced over time due to depletion and therefore artificial lift is needed to uplift the gas to the surface which might increase the extraction cost for each additional unit extracted. Also, because the quantities of gas extracted need further processing and refinery before its final use, firms would face additional cost for each additional unit extracted. We also found that the taxes are inversely related to the firm's cost of extraction although it provides government revenue for society's benefits in the country. Higher level of taxes may provide more government revenue in the short

period but will shorten the time for firms to extract the resource to maximize their sum of cash flow and hence lead to resource inefficiencies in the long term.

The estimate of the average shadow price of the natural gas of \$ 6.33 per million BTU is closer to the actual domestic price of gas which lies between \$ 6 and \$ 12 per million BTU in the country. The study further compared the shadow price with global price of natural gas in key gas markets in the world. We discovered that the average shadow price of \$ 6.33 per million BTU in the country is lower compared to European international gas market price having an average actual price of \$ 10.11 per million BTU (see appendix 2) for the period between 2010 and 2014. Therefore we conclude that, the proportion of resource appreciation which is the shadow price has not been taken into account in fixing the gas price in the country. Although, it is not the only factor in resource price determination in most resource markets, the shadow price provides the value and appreciation of the resource and thus the value should not be underestimated. The study further argues that the comparison of domestic with international gas market is useful in determining and designing the baseline natural gas prices for the domestic market, regional markets and future LNG business in the country. Furthermore, we argue that the part of revenues from the shadow price should be reinvested into capital generating activities for the benefits future generations too.

Results from this study found that the natural gas data do not conform to Hotelling's principle and that natural gas extraction in the country is not made in a manner consistent with the theory. Thus, the production decisions made by natural gas firms are not economically optimal according to the theory. We can conclude that, the behavior of firms

extracting and producing natural gas in Tanzania are operating at sub-optimal level according to the Hotelling's dynamic optimality condition.

Finally we found that the firms were not operating on the dynamic optimal path. At 8% discount rate, the optimal cost path shows the cost was declining over the period. The optimal extraction profile shows the costs is reduced as gas quantities are extracted although the stock of reserves is still higher given the slower rates of extraction. It shows that the optimal path of natural gas extraction is downward sloping, and hence the discount factor provides an incentive to the firms to extract more quick. However, when discount rate is higher than 8%, the optimal extraction path is also downward sloping but is steeper than when discount rate is 8% because future discounted sum of cost are discounted more. Therefore firms would also have an incentive to extract more and quicker because of higher discounting factor and lower cost of extraction. Then there is possibility of unsustainable profile which would lead to resource inefficiencies, limited revenue and higher depletion rates which may bring less return in long run.

### **6.3 Policy Recommendations**

Based on the findings, the following policy recommendations are offered to ensure optimal and sustainable extraction of natural gas in Tanzania.

The study found that the firm's extraction cost increases with increasing quantities for which the gas firms are not operating on the dynamic optimal path and rather operate at sub-optimal level. Therefore, the study recommends that the government institutions and operating firms should not only re-examine and adjust the taxes in natural gas sector such as corporate tax and royalties' rates, but also consider other factors such as firms' transfer pricing, undervaluation of receipts and over-invoicing or overestimation of companies

equipments, as these might cause increasing cost to the firm's operations. Hence, it is imperative to review and assess these factors since they have a likelihood of affecting cost of extraction and possibly alter optimal dynamic path of gas extraction in the country.

We found that the choice discount rate plays a significant role in obtaining the resource optimal dynamic path. We suggest that, the government institutions should envisage to make clear and suitable policies to lower the social time path of extraction so as to ensure resource sustainability. However, we further recommend the re-examination of other policy issues that would possibly affect dynamic paths other than choice of discount rate. These factors might emanate from either government policies, returns from investments, firms strategies in production as well as company's risks and cost sharing. In addition to that, to ensure firms optimal rate and optimal dynamic path according to the Hotelling prediction, government policies should be geared towards providing incentives to the operating firms such as lower taxes or tax exemptions on the importation of technology in the country so that the firms can operate on the optimal paths.

Moreover, policy makers should consider the crucial component of shadow price when designing the actual market price for natural gas in the country. The study suggests that natural gas market price would be considered appropriate if it takes into account the scarcity of the resource overtime together with other policy components such as taxes that make up the market price of the gas. This will ensure steady flow of government revenue and competitiveness to the domestic, regional and international gas markets.

In addition to that, since the country is expecting to be a major supplier of LNG from 2020, there is also an opportunity for government as a regulatory institution to set or bargain for the market prices of the resource considering the returns to the country and life of the

reserves. Our study suggests that, when the gas prices are set in the country, it is imperative that the international gas prices and markets performances especially of European and Japan LNG markets form the basis. The country is expecting to supply gas to the growing markets in Asia especially in China, Singapore and Indonesia. Since most of these Asian countries take their baseline price from the Japanese and European gas market prices. In determining prices our study suggests that, gas firms and government institutions should design prices that will safeguard their investment returns and flow of revenue while ensuring constant supply of gas to the international markets.

Since the natural gas sector in Tanzania is at its infant and growing stage, we suggest that, policies, plans and strategies should be formulated and revised overtime to compliment sectorial needs. The transparency and flexibility of the policies, fiscal regimes as well as appropriate institutional mechanisms can attract more FDI and ensure fair share of the resource proceeds to the government and citizens.

The developmental impact of the sector as well as the benefit to the country depends on how royalties, taxes and other extraction charges are determined, legislated and collected. A portion of proceeds can be allocated and invested in sectors that expand both physically and human capital. Such investments can be in sectors like health, roads and education. The capital regenerating activities will generate significant output to the economy even when the resource is depleted. For example, Botswana has established a PULA fund in which proceeds from Diamonds are put. The fund serves as a buffer stock from price volatility and finance development activities in the country, that have effects on both current and future generation. If such a fund is established for the gas sector, then the

current and future generation will get benefit which will ensures growth of the Tanzanian economy.

### **6.3.1 Areas of further studies**

Since there is ongoing natural gas discovery in the country to-date, it would be interesting to conduct a study, estimating the cost of discoveries, field development costs as well as forecasting extraction costs of natural gas resource.

Further studies should also focus on the assessment of other factors affecting the dynamic optimal path other than the choice of discount rate (which would be equated to market interest rate). Assessment of other factors effecting dynamic path would help social planner in bringing operating firms into social optimal way of resource extraction.

### **6.4 Limitations of the study**

The major drawback of this study is concerned with data acquisition. Only five years were selected for the two operating firms because of limitations in obtaining data on cost of extracting natural gas in Tanzania. Initial years of gas production such as from 2004-2009 would have been interesting additions in examining extraction paths and testing the nonrenewable theory but limited data availability made it impossible. As a result, the study has to settle on 2010-2014 as the study period.

Since the data collected and used were secondary, statistical problems and other fundamental errors such as printing errors can sometimes affect the reliability of the findings and as a result any problem related to such data- set cannot be ruled out.

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## APPENDICES

## Appendix 1: Random Effects (RE) Model Estimated Results

Estimated Model	(RE)	(RE)	(RE)	(RE)
Type of cost Function	(Unrestricted)	(Restricted)	(Average cost)	(Gross cost)
		$\beta_q = -\beta_z$	$\ln C - \ln z$	$\ln z=0$
VARIABLES	FCU	FCR	FCA	GC
Gross production, q	-0.426 (2.310)	-4.156* (2.220)	0.183 (0.559)	0.332 (0.609)
Refined quantities, z	0.771 (2.266)	0.268 (0.592)		
Remaining reserves, R	-177.3*** (52.12)	-158.1*** (52.29)	-53.26 (72.36)	-176.8*** (51.89)
Corporate taxes (corpt)	0.0161 (0.112)	0.0109 (0.109)	0.0289 (0.0987)	0.0242 (0.109)
Royalties(roy)	-0.572*** (0.200)	-0.563*** (0.197)	-0.309* (0.185)	-0.570*** (0.199)
$\alpha_{2011}$	0.753*** (0.211)	0.813*** (0.210)	0.477** (0.190)	0.752*** (0.210)
$\alpha_{2012}$	0.833*** (0.201)	0.831*** (0.197)	0.659*** (0.191)	0.832*** (0.200)
$\alpha_{2013}$	1.236*** (0.276)	1.255*** (0.272)	0.979*** (0.256)	1.233*** (0.275)
$\alpha_{2014}$	1.309*** (0.250)	1.341*** (0.246)	1.158*** (0.241)	1.308*** (0.249)
Constant	17.80*** (1.967)	17.86*** (1.936)	10.08*** (1.794)	17.78*** (1.959)
Observations	118	118	118	118
R-squared			0.195	
Number of firm	2	2	2	2

Standard errors in parentheses

\*\*\* p&lt;0.01, \*\* p&lt;0.05, \* p&lt;0.1

Source: Author's computation.

**Appendix 2: WORLD NATURAL GAS PRICES (USD per million BTU)**

YEARS	UNITED STATES	UNITED KINGDOM	JAPAN
2010	4.4	8.3	10.8
2011	4	10.5	14.7
2012	2.8	11.5	16.6
2013	3.7	11.8	16
2014	4.4	10.1	15.8
(forecasts)2015	4	8.5	11

Source: EIU Economic and Commodity Forecast &  
World Bank Commodity Price Forecasts (Nominal USD)

**Appendix 3: Optimal Extraction Path for Songo Songo Natural gas field at 6% Discount rate**

Discount rate ( $\delta$ ) = 0.06			Discount factor ( $\rho$ )= 0.94340					
Initial values before optimization						Optimized values		
Months 2010-2014	Initial total cost	Quantities extracted	Total reserves	Initial total reserves	Present value net cost	Optimized quantities	Optimized reserves	Optimal cost path
1	12.64	7.69	12.855	12.86	857.82	0.48	12.86	156.04
2	12.85	7.65	12.850	5.17	728.82	0.48	12.38	144.13
3	12.92	7.73	12.844	5.20	703.91	0.46	12.37	136.54
4	12.82	7.64	12.838	5.12	644.43	0.47	12.38	128.03
5	12.92	7.67	12.833	5.20	618.71	0.46	12.36	121.42
6	12.51	7.74	12.826	5.16	574.09	0.48	12.37	111.16
7	12.88	7.85	12.820	5.09	570.79	0.47	12.34	107.60
8	12.87	7.83	12.813	4.97	535.03	0.46	12.35	101.42
9	12.53	7.77	12.806	4.98	484.69	0.49	12.35	93.41
10	12.97	7.86	12.799	5.04	483.97	0.48	12.32	90.86
11	13.20	7.75	12.793	4.94	452.23	0.49	12.32	87.39
12	13.84	7.70	12.787	5.04	442.28	0.45	12.30	85.99
13	12.91	7.69	12.780	5.09	389.15	0.47	12.34	76.04
14	12.75	7.65	12.774	5.09	358.45	0.50	12.31	70.76
15	13.16	7.81	12.767	5.13	362.64	0.46	12.28	68.57
16	12.83	7.72	12.761	4.96	326.24	0.48	12.31	63.32
17	13.26	7.63	12.755	5.04	311.51	0.46	12.28	61.49
18	13.05	7.87	12.747	5.12	306.73	0.48	12.29	57.26
19	13.44	7.97	12.739	4.88	303.92	0.48	12.26	55.48
20	13.69	7.99	12.730	4.77	292.85	0.45	12.26	53.21
21	13.05	7.93	12.722	4.74	259.76	0.47	12.28	47.98
22	12.89	7.98	12.713	4.79	244.78	0.46	12.25	44.60
23	12.65	7.91	12.705	4.74	223.05	0.47	12.25	41.30
24	12.84	8.00	12.696	4.79	218.38	0.47	12.23	39.49
25	13.01	7.95	12.687	4.69	205.76	0.46	12.23	37.69
26	12.87	7.94	12.678	4.74	191.71	0.48	12.23	35.24
27	13.33	8.03	12.669	4.74	191.39	0.44	12.20	34.28
28	12.78	8.01	12.659	4.64	171.90	0.47	12.23	31.12

29	12.78	8.00	12.650	4.65	161.88	0.49	12.19	29.33
30	13.27	8.02	12.640	4.65	159.16	0.48	12.16	28.62
31	13.49	8.05	12.630	4.62	153.91	0.47	12.16	27.42
32	13.35	8.05	12.619	4.58	143.69	0.46	12.16	25.59
33	12.89	8.01	12.609	4.56	129.58	0.51	12.16	23.42
34	14.05	8.07	12.599	4.60	135.00	0.41	12.10	23.77
35	12.40	7.99	12.589	4.53	110.41	0.46	12.19	20.00
36	12.43	8.04	12.578	4.59	105.55	0.48	12.13	18.86
37	13.04	8.03	12.567	4.54	104.32	0.44	12.10	18.55
38	12.72	7.93	12.558	4.53	93.59	0.46	12.13	17.15
39	12.78	8.02	12.547	4.63	90.76	0.46	12.10	16.21
40	12.99	7.95	12.537	4.53	85.61	0.46	12.08	15.53
41	13.03	7.94	12.527	4.58	80.74	0.45	12.07	14.67
42	12.62	7.98	12.516	4.59	74.60	0.48	12.08	13.44
43	12.81	8.02	12.505	4.53	71.99	0.49	12.04	12.83
44	13.14	7.98	12.494	4.48	69.02	0.48	12.02	12.39
45	13.14	7.98	12.483	4.51	65.08	0.46	12.02	11.67
46	12.71	8.02	12.471	4.50	59.92	0.47	12.02	10.66
47	12.54	7.94	12.460	4.45	54.72	0.51	12.01	9.94
48	13.78	8.01	12.449	4.52	57.79	0.47	11.95	10.24
49	13.97	8.01	12.437	4.44	55.11	0.43	11.97	9.78
50	13.01	7.89	12.426	4.43	47.11	0.43	12.00	8.61
51	12.64	7.97	12.414	4.54	44.09	0.46	12.00	7.90
52	13.19	7.79	12.405	4.44	41.46	0.42	11.95	7.73
53	12.76	7.85	12.394	4.62	38.50	0.48	11.98	7.10
54	13.55	7.92	12.383	4.55	39.20	0.42	11.92	7.04
55	12.72	7.97	12.371	4.46	35.04	0.51	11.97	6.31
56	13.58	7.96	12.359	4.41	35.26	0.44	11.86	6.27
57	12.70	7.93	12.347	4.39	30.86	0.56	11.92	5.61
58	12.99	7.90	12.335	4.41	29.61	0.62	11.79	5.39
59	13.96	7.90	12.323	4.43	30.00	0.42	11.72	5.34
60	13.27	7.92	12.310	4.42	27.00	12.31	11.90	65.73
				4.39	<b>13,915.55</b>		0.00	<b>2,684.97</b>

Source: Author's computation

#### Appendix 4: Optimal Extraction Path for Mnazi Bay Natural gas field at 6% Discount rate

Discount ( $\delta$ )= 0.06		Discount factor ( $\rho$ )= 0.943396						
Initial values before Optimization						Optimized values		
Months 2010-2014	Initial total cost	Quantities extracted	Total reserves	Initial net reserves	Present value net cost	Optimized quantities	Optimized reserves	Optimal cost path
1	11.83	3.36	12.608	12.61	266.40	0.48	12.61	143.32
2	12.06	3.30	12.608	9.25	216.34	0.45	12.13	132.35
3	11.40	3.57	12.608	9.31	210.97	0.49	12.16	118.72
4	11.92	3.54	12.608	9.04	203.82	0.44	12.12	116.25
5	11.14	3.50	12.608	9.07	177.63	0.53	12.17	103.66
6	12.53	3.53	12.608	9.11	190.32	0.32	12.08	107.63
7	8.58	3.36	12.608	9.08	116.32	0.66	12.28	72.57

8	11.91	3.52	12.608	9.25	161.81	0.49	11.95	91.14
9	12.39	3.58	12.608	9.09	160.47	0.46	12.12	90.41
10	12.14	3.99	12.607	9.03	169.03	0.46	12.15	83.72
11	11.75	4.01	12.607	8.62	152.68	0.50	12.15	76.77
12	12.53	3.98	12.607	8.60	152.47	0.44	12.10	76.62
13	11.73	4.00	12.607	8.62	135.53	0.49	12.17	68.23
14	12.27	3.82	12.607	8.60	125.94	0.45	12.11	66.85
15	11.67	3.97	12.606	8.79	119.55	0.48	12.16	60.36
16	12.00	3.91	12.606	8.64	113.20	0.49	12.12	58.38
17	12.32	4.06	12.606	8.69	115.07	0.47	12.12	56.44
18	12.15	4.15	12.606	8.55	109.59	0.48	12.14	52.66
19	12.44	4.07	12.606	8.46	102.91	0.47	12.12	50.75
20	12.37	4.06	12.606	8.53	96.44	0.51	12.14	47.81
21	13.33	4.02	12.605	8.55	96.77	0.45	12.10	48.23
22	12.66	4.08	12.605	8.59	88.57	0.45	12.16	43.44
23	12.17	4.06	12.605	8.53	79.76	0.55	12.15	39.65
24	14.07	3.94	12.605	8.54	83.57	0.41	12.06	42.51
25	12.49	3.96	12.605	8.67	70.80	0.47	12.19	36.11
26	12.56	3.99	12.604	8.65	67.71	0.46	12.13	34.08
27	12.45	4.00	12.604	8.62	63.50	0.49	12.14	31.95
28	12.97	3.95	12.604	8.61	61.52	0.47	12.11	31.31
29	12.95	4.09	12.604	8.65	60.62	0.47	12.13	29.54
30	13.03	3.98	12.604	8.52	55.23	0.48	12.13	28.03
31	13.11	4.03	12.603	8.62	53.48	0.46	12.13	26.57
32	12.65	4.01	12.603	8.58	48.38	0.49	12.14	24.28
33	13.16	4.03	12.603	8.59	47.75	0.48	12.11	23.74
34	13.24	4.09	12.603	8.57	46.19	0.42	12.13	22.47
35	11.84	4.08	12.603	8.51	38.80	0.51	12.18	19.16
36	12.86	4.12	12.603	8.52	40.19	0.47	12.09	19.44
37	12.94	3.92	12.602	8.49	35.70	0.47	12.13	18.52
38	13.09	3.90	12.602	8.69	34.18	0.47	12.13	17.66
39	13.21	4.09	12.602	8.70	34.63	0.46	12.13	16.80
40	12.94	4.10	12.602	8.51	31.82	0.47	12.14	15.56
41	13.05	4.13	12.602	8.50	30.62	0.47	12.13	14.78
42	13.02	4.08	12.601	8.47	28.26	0.47	12.13	13.92
43	13.01	4.09	12.601	8.52	26.79	0.47	12.13	13.11
44	12.86	4.09	12.601	8.51	24.96	0.48	12.13	12.24
45	12.82	4.10	12.601	8.51	23.55	0.48	12.12	11.51
46	12.97	4.17	12.601	8.50	23.00	0.50	12.12	10.99
47	13.54	4.18	12.600	8.43	22.68	0.47	12.10	10.78
48	13.25	4.19	12.600	8.42	20.97	0.47	12.13	9.99
49	13.18	4.13	12.600	8.41	19.33	0.45	12.13	9.35
50	12.70	3.94	12.600	8.47	16.53	0.48	12.14	8.53
51	13.13	4.14	12.600	8.66	17.35	0.47	12.12	8.30
52	13.18	4.10	12.599	8.46	16.10	0.46	12.13	7.86
53	13.19	4.17	12.599	8.50	15.59	0.49	12.14	7.44
54	13.93	4.14	12.599	8.43	15.31	0.42	12.11	7.36
55	12.78	4.19	12.599	8.46	13.50	0.47	12.18	6.43
56	12.97	4.22	12.598	8.40	13.03	0.49	12.13	6.13
57	13.47	4.19	12.598	8.37	12.61	0.44	12.11	5.99

58	12.49	4.28	12.598	8.41	11.39	0.50	12.16	5.28
59	12.70	4.27	12.598	8.31	10.84	0.54	12.10	5.06
60	14.54	4.24	12.597	8.33	11.61	12.60	12.05	75.25
				8.35	<b>4,609.69</b>		0.00	<b>2,493.99</b>

Source: Author's computation

### Appendix 5: Optimal Extraction Path for Songo Songo Natural gas field at 10% Discount rate

Discount rate ( $\delta$ )= 0.1						Discount factor (Rho)= 0.90909		
Initial values before Optimization						Optimized values		
Months 2010-2014	Initial total cost	Quantities extracted	Total reserves	Initial net reserves	Present value net cost	Optimized quantities	Optimized reserves	Optimal cost path
1	12.64	7.69	12.855	12.855	826.62	0.46	12.86	150.19
2	12.85	7.65	12.850	5.17	676.78	0.45	12.39	133.77
3	12.92	7.73	12.844	5.20	629.88	0.44	12.40	122.25
4	12.82	7.64	12.838	5.12	555.68	0.47	12.40	110.51
5	12.92	7.67	12.833	5.20	514.11	0.46	12.37	100.93
6	12.51	7.74	12.826	5.16	459.69	0.47	12.37	88.92
7	12.88	7.85	12.820	5.09	440.42	0.46	12.36	83.10
8	12.87	7.83	12.813	4.97	397.82	0.45	12.35	75.41
9	12.53	7.77	12.806	4.98	347.28	0.47	12.36	66.89
10	12.97	7.86	12.799	5.04	334.16	0.46	12.33	62.73
11	13.20	7.75	12.793	4.94	300.88	0.48	12.34	58.18
12	13.84	7.70	12.787	5.04	283.56	0.42	12.31	55.06
13	12.91	7.69	12.780	5.09	240.43	0.44	12.37	46.96
14	12.75	7.65	12.774	5.09	213.41	0.48	12.34	42.21
15	13.16	7.81	12.767	5.13	208.05	0.45	12.29	39.36
16	12.83	7.72	12.761	4.96	180.36	0.47	12.32	35.00
17	13.26	7.63	12.755	5.04	165.96	0.45	12.29	32.77
18	13.05	7.87	12.747	5.12	157.47	0.47	12.30	29.40
19	13.44	7.97	12.739	4.88	150.35	0.46	12.27	27.42
20	13.69	7.99	12.730	4.77	139.61	0.41	12.28	25.34
21	13.05	7.93	12.722	4.74	119.33	0.46	12.32	22.09
22	12.89	7.98	12.713	4.79	108.36	0.47	12.27	19.78
23	12.65	7.91	12.705	4.74	95.15	0.47	12.24	17.59
24	12.84	8.00	12.696	4.79	89.77	0.45	12.24	16.22
25	13.01	7.95	12.687	4.69	81.51	0.45	12.25	14.95
26	12.87	7.94	12.678	4.74	73.18	0.45	12.24	13.43
27	13.33	8.03	12.669	4.74	70.40	0.45	12.23	12.64
28	12.78	8.01	12.659	4.64	60.93	0.46	12.22	11.02
29	12.78	8.00	12.650	4.65	55.29	0.47	12.20	10.01
30	13.27	8.02	12.640	4.65	52.39	0.46	12.18	9.42
31	13.49	8.05	12.630	4.62	48.82	0.45	12.18	8.70
32	13.35	8.05	12.619	4.58	43.92	0.46	12.18	7.84
33	12.89	8.01	12.609	4.56	38.17	0.51	12.16	6.89
34	14.05	8.07	12.599	4.60	38.32	0.44	12.10	6.76
35	12.40	7.99	12.589	4.53	30.20	0.45	12.16	5.45
36	12.43	8.04	12.578	4.59	27.82	0.45	12.14	4.96

37	13.04	8.03	12.567	4.54	26.49	0.39	12.12	4.71
38	12.72	7.93	12.558	4.53	22.90	0.41	12.17	4.20
39	12.78	8.02	12.547	4.63	21.40	0.42	12.15	3.83
40	12.99	7.95	12.537	4.53	19.45	0.43	12.13	3.53
41	13.03	7.94	12.527	4.58	17.68	0.43	12.11	3.22
42	12.62	7.98	12.516	4.59	15.74	0.47	12.10	2.84
43	12.81	8.02	12.505	4.53	14.64	0.47	12.05	2.61
44	13.14	7.98	12.494	4.48	13.53	0.44	12.04	2.43
45	13.14	7.98	12.483	4.51	12.29	0.39	12.05	2.20
46	12.71	8.02	12.471	4.50	10.90	0.33	12.09	1.93
47	12.54	7.94	12.460	4.45	9.60	0.30	12.14	1.74
48	13.78	8.01	12.449	4.52	9.77	0.27	12.16	1.74
49	13.97	8.01	12.437	4.44	8.97	0.18	12.18	1.60
50	13.01	7.89	12.426	4.43	7.39	0.11	12.26	1.36
51	12.64	7.97	12.414	4.54	6.67	0.15	12.31	1.21
52	13.19	7.79	12.405	4.44	6.04	0.15	12.27	1.14
53	12.76	7.85	12.394	4.62	5.41	0.29	12.26	1.01
54	13.55	7.92	12.383	4.55	5.30	0.24	12.11	0.96
55	12.72	7.97	12.371	4.46	4.57	0.51	12.15	0.83
56	13.58	7.96	12.359	4.41	4.43	0.50	11.86	0.79
57	12.70	7.93	12.347	4.39	3.74	0.88	11.86	0.70
58	12.99	7.90	12.335	4.41	3.45	1.35	11.46	0.69
59	13.96	7.90	12.323	4.43	3.37	0.70	10.98	0.58
60	13.27	7.92	12.310	4.42	2.93	12.31	11.63	7.11
				4.39	<b>8,512.74</b>		0.00	<b>1,627.11</b>

Source: Author's computation

### Appendix 6: Optimal Extraction Path for Mnazi Bay Natural gas field at 10% Discount rate

Discount rate ( $\delta$ )= 0.1						Discount factor ( $\rho$ )= 0.90909		
Initial values before optimization						Optimized values		
Months 2010-2014	Initial total cost	Quantities extracted	Total reserves	Initial net reserves	Present value net cost	Optimized quantities	Optimized reserves	Optimal cost path
1	11.83	3.36	12.608	12.61	256.71	0.46	12.61	137.93
2	12.06	3.30	12.608	9.25	200.89	0.43	12.15	122.92
3	11.40	3.57	12.608	9.31	188.78	0.47	12.18	106.24
4	11.92	3.54	12.608	9.04	175.75	0.42	12.13	100.26
5	11.14	3.50	12.608	9.07	147.60	0.51	12.18	86.11
6	12.53	3.53	12.608	9.11	152.39	0.31	12.10	86.27
7	8.58	3.36	12.608	9.08	89.75	0.63	12.30	55.93
8	11.91	3.52	12.608	9.25	120.32	0.47	11.97	67.80
9	12.39	3.58	12.608	9.09	114.98	0.45	12.13	64.79
10	12.14	3.99	12.607	9.03	116.71	0.44	12.16	57.79
11	11.75	4.01	12.607	8.62	101.59	0.49	12.17	51.11
12	12.53	3.98	12.607	8.60	97.76	0.43	12.12	49.13
13	11.73	4.00	12.607	8.62	83.74	0.47	12.18	42.13
14	12.27	3.82	12.607	8.60	74.98	0.44	12.13	39.85
15	11.67	3.97	12.606	8.79	68.59	0.46	12.16	34.58

16	12.00	3.91	12.606	8.64	62.58	0.47	12.15	32.30
17	12.32	4.06	12.606	8.69	61.30	0.45	12.14	30.08
18	12.15	4.15	12.606	8.55	56.26	0.48	12.16	27.07
19	12.44	4.07	12.606	8.46	50.91	0.45	12.13	25.07
20	12.37	4.06	12.606	8.53	45.98	0.48	12.16	22.78
21	13.33	4.02	12.605	8.55	44.46	0.43	12.13	22.18
22	12.66	4.08	12.605	8.59	39.21	0.46	12.18	19.26
23	12.17	4.06	12.605	8.53	34.03	0.53	12.15	16.88
24	14.07	3.94	12.605	8.54	34.35	0.40	12.08	17.49
25	12.49	3.96	12.605	8.67	28.05	0.47	12.20	14.32
26	12.56	3.99	12.604	8.65	25.85	0.48	12.14	13.02
27	12.45	4.00	12.604	8.62	23.36	0.49	12.13	11.75
28	12.97	3.95	12.604	8.61	21.81	0.45	12.11	11.08
29	12.95	4.09	12.604	8.65	20.71	0.45	12.15	10.08
30	13.03	3.98	12.604	8.52	18.18	0.42	12.15	9.21
31	13.11	4.03	12.603	8.62	16.96	0.41	12.18	8.44
32	12.65	4.01	12.603	8.58	14.79	0.48	12.19	7.44
33	13.16	4.03	12.603	8.59	14.07	0.48	12.12	7.00
34	13.24	4.09	12.603	8.57	13.11	0.45	12.12	6.39
35	11.84	4.08	12.603	8.51	10.61	0.53	12.16	5.24
36	12.86	4.12	12.603	8.52	10.59	0.48	12.08	5.12
37	12.94	3.92	12.602	8.49	9.07	0.45	12.12	4.69
38	13.09	3.90	12.602	8.69	8.37	0.44	12.16	4.32
39	13.21	4.09	12.602	8.70	8.17	0.42	12.16	3.96
40	12.94	4.10	12.602	8.51	7.23	0.44	12.18	3.54
41	13.05	4.13	12.602	8.50	6.70	0.44	12.16	3.24
42	13.02	4.08	12.601	8.47	5.96	0.48	12.16	2.94
43	13.01	4.09	12.601	8.52	5.45	0.49	12.13	2.67
44	12.86	4.09	12.601	8.51	4.89	0.52	12.11	2.40
45	12.82	4.10	12.601	8.51	4.45	0.53	12.08	2.17
46	12.97	4.17	12.601	8.50	4.19	0.54	12.07	2.00
47	13.54	4.18	12.600	8.43	3.98	0.50	12.06	1.89
48	13.25	4.19	12.600	8.42	3.54	0.48	12.10	1.68
49	13.18	4.13	12.600	8.41	3.15	0.42	12.12	1.52
50	12.70	3.94	12.600	8.47	2.59	0.38	12.18	1.33
51	13.13	4.14	12.600	8.66	2.62	0.37	12.22	1.26
52	13.18	4.10	12.599	8.46	2.35	0.34	12.23	1.15
53	13.19	4.17	12.599	8.50	2.19	0.36	12.26	1.05
54	13.93	4.14	12.599	8.43	2.07	0.29	12.24	1.00
55	12.78	4.19	12.599	8.46	1.76	0.37	12.31	0.84
56	12.97	4.22	12.598	8.40	1.64	0.41	12.23	0.77
57	13.47	4.19	12.598	8.37	1.53	0.41	12.18	0.73
58	12.49	4.28	12.598	8.41	1.33	0.54	12.19	0.62
59	12.70	4.27	12.598	8.31	1.22	0.93	12.06	0.59
60	14.54	4.24	12.597	8.33	1.26	12.60	11.67	8.13
				8.35	<b>2,733.36</b>		0.00	<b>1,479.53</b>

Source: Author's computation