PAU Pan African University
Institute of Water
and Energy Sciences
Nurturing Quality, Exemplifying Excellence

PAN-AFRICAN UNIVERSITY
INSTITUTE FOR WATER AND ENERGY SCIENCES
(including CLIMATE CHANGE)

Master Dissertation

Submitted in partial fulfillment of the requirements for the Master degree in

ENERGY ENGINEERING

Presented by

Chipo Ruth Nomhle SITOTOMBE

Modelling Renewable Energy Integration “A System Dynamics Approach” Case of Tanzania

Defended on 03/09/2018 Before the Following Committee:

Chair	Brahim Cherki	Prof.	University of Tlemcen, Algeria
Supervisor	Dénes Csala	Dr.	Lancaster University (UK)
External Examiner	Abdallah Khellaf	Dr.	Centre de Dévelopment des Energies Renouvables,
Internal Examiner	Abdellah Benyoucef	Dr.	Pan African University (PAUWES)

Modelling Renewable Energy Integration

“A System Dynamics Approach”

Case of Tanzania

DECLARATION

I, *Sitotombe Chipo Ruth Nomhle* hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

Signature: Sitotombe

Date: 22-Sept-2018

Supervisor's Signature: Csala Dénes

Date: 10-Sep-2018

CERTIFICATION

I **Dénes Csala** certify that this final version of the master thesis was submitted with my approval and that all corrections were added as recommended by the examination committee.

Signature: Csala Dénes

Date: 10-Sep-2018

Student's Signature: Sitotombe

Date: 22-Sept-2018

ABSTRACT

The lack of access to affordable modern energy that is evident in most Sub-Saharan countries amidst other challenges which include climate change, high population growth rates, urbanization, depleting fossil fuels, to mention just but a few, raises the need for accelerated actions to be taken towards achieving sustainable energy systems. This study uses a system dynamic modelling approach to justify the need for more efforts towards renewable energy integration. A physical model that incorporates the social, economic, technical, political and environmental aspects of Tanzania's energy system is prepared; to calculate energy price ratios of three electricity generating technologies; natural gas turbines hydropower and other renewables (which are the target focus in this study and are combined as solar PV and wind). In addition, the model is used to determine the energy demand response to the energy price ratio changes of the technologies over a 30-year time horizon. Results of the modelling exercise show that natural gas and hydro power technologies which are currently contributing the majority share in the electricity mix of Tanzania and thus driving the current electricity price in the country will experience a very small decrease in the energy price ratios during the modelling period. The price ratios of these 2 technologies will remain just below 1 even with high levels of commitment from Tanzanian authorities to promote them, which shows that relying on these generating technologies will result in a small decrease in the electricity price. On the other hand, renewables experience a significant decrease in the energy price ratio. The energy price ratio of renewables is expected to reduce and match that of hydropower and natural gas and eventually reach an estimated value of 0.5 which suggests that deploying renewable electricity in Tanzania could result in the electricity price in the country cutting by half. The low energy price ratios of renewable energy results in an estimated 30% increase in energy demand for renewables and this resultant high energy demand values indicate that, more electricity consumers especially the low-income consumers (which make up the largest share of Tanzania's population) will be attracted to renewable electricity. Hence, renewable electricity can play a major role in fostering access to affordable energy in Tanzania and therefore, more commitment by Tanzanian authorities is required to attain a reduced electricity price ratio for renewable electricity sooner in order to accelerate renewable energy deployment.

Résumé

Le manque d'accès à une énergie moderne et abordable dans la plupart des pays subsahariens face à d'autres défis tels que le changement climatique, les taux de croissance élevés de la population, l'urbanisation, l'épuisement des combustibles fossiles, etc. soulèvent la nécessité de prise d'actions accélérées pour atteindre des systèmes énergétiques durables. Cette étude utilise une approche de modélisation de la dynamique du système pour justifier le besoin de plus d'efforts pour l'intégration de l'énergie renouvelable. Un modèle physique intégrant les aspects sociaux, économiques, techniques, politiques et environnementaux du système énergétique Tanzanien est préparé ; calculer les ratios de prix de l'énergie de trois technologies de production d'électricité ; turbines à gaz naturel hydroélectricité et autres énergies renouvelables (qui sont la cible de cette étude et sont combinées comme le solaire PV et le vent). En outre, le modèle est utilisé pour déterminer la réponse de la demande d'énergie aux changements du rapport des prix de l'énergie des technologies sur un horizon temporel de 30 ans. Les résultats de l'exercice de modélisation montrent que les technologies du gaz naturel et de l'hydroélectricité, qui contribuent actuellement majoritairement au mix électrique de la Tanzanie et entraînent ainsi le prix actuel de l'électricité dans le pays, connaîtront une très faible diminution des ratios période. Les ratios de prix de ces deux technologies resteront juste en dessous de 1 même avec un niveau élevé d'engagement des autorités tanzaniennes à les promouvoir, ce qui montre que le recours à ces technologies génératrices entraînera une légère baisse du prix actuel de l'électricité. D'autre part, les énergies renouvelables connaissent une baisse significative du ratio des prix de l'énergie. Le rapport des prix des énergies renouvelables devrait réduire et égaler celui de l'hydroélectricité et du gaz naturel et atteindre une valeur estimée à 0,5, ce qui suggère que le déploiement d'électricité renouvelable en Tanzanie pourrait entraîner une baisse de moitié du prix de l'électricité dans le pays. Les faibles prix des énergies renouvelables entraînent une augmentation estimée de 30% de la demande énergétique pour les énergies renouvelables, ce qui indique que plus de consommateurs d'électricité, en particulier les consommateurs à faible revenu (qui représentent la plus grande partie de la population tanzanienne) sera attirée par l'électricité renouvelable. Par conséquent, l'électricité renouvelable peut jouer un rôle majeur dans la promotion de l'accès à une énergie abordable en Tanzanie et, par conséquent, les autorités tanzaniennes doivent s'engager davantage à réduire le prix de l'électricité renouvelable pour accélérer le déploiement des énergies renouvelables

ACKNOWLEDGEMENT

The author acknowledges with thanks the dedicated assistance and personal commitment of Dénes Csala (PhD), of the Lancaster University, UK, the thesis supervisor and Dr William Blyth of Chatham House, UK, the mentor provided by International Support Network for African Development (ISNAD- Africa) in the 2018 Mentoring for Research Programme. Both Dénes and Dr William have been very supportive and active in stimulating discussions and giving out constructive reviews. They continuously motivated me and patiently guided me throughout the undertaking of this thesis. The successful completion of this work owes a lot to them.

A special note of thanks goes to the Pan African University of Water and Energy Sciences (PAUWES) Administration and the sponsors of the master program and research, African Union, GIZ and KFW for awarding me this amazing opportunity to become part of a program that equips young African minds with relevant skills to deal with Africa’s energy crisis.

Deep gratitude goes to my friends and family for their undying love and support throughout this journey.

Above all, many thanks to the Lord for his love, mercy, guidance and for making this dream a reality.

CONTENTS

LIST OF ABBREVIATIONS

RE	Renewable Energy
IRENA	International Renewable Energy Agency
IEA	International Energy Agency
EIA	Energy Information Administration
IPP	Independent Power Producers
EPP	Emergency Power Producers
SPP	Small Power Producers
GDP	Growth Domestic Product
TANESCO	Tanzania Electricity Supply Company
MEM	Ministry of Energy and Mines
SAPP	Southern African Power Pool
EWURA	Energy and Water Utility Regulatory Authority
IDO	Industrial Diesel Oil
EAPP	East African Power Pool
REA	Rural Energy Agency

LIST OF UNITS

kW	kilowatts
kWh	kilowatt-hour
Mtoe	million tons of oil equivalent
Btu	British Thermal Units
mmBtu	million British Thermal Units
c/kWh	cents per kilowatt-hour
MW	megawatts
GW	gigawatts
GWh	gigawatt-hours
MWh	megawatt/hours
MJ	megajoules
Tcf	trillion cubic feet

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES

1 INTRODUCTION

1.1 Background

Modern energy is one of the key drivers to sustained economic growth and an important tool for improved livelihoods. Despite the vast energy resources, Sub-Saharan Africa remains a part of the world with the largest number of people without access to modern energy than any other world region. An estimated two-thirds of Sub-Saharan Africa's population do not have access to modern energy and rely on traditional fuels for energy (OECD/IEA, 2014) while those that have access often face high prices for supply that is poor quality and rely on under-developed systems that are not able to meet their needs.

On the other hand, Africa has the fastest growing populations and the highest urbanization rates. According to (Heilig, 2017), the share of Africa's population in the total population will more than triple between 1950 and 2100 - from 9% to 39%. This alarming growth rate is resulting in the rapid increase of population without access to modern energy in Sub-Saharan Africa. In addition, most countries in the region are undergoing a period of economic growth and transformation which needs to be fueled by large amounts of energy. Therefore, Sub-Saharan Africa is faced with the problem of having to provide for its region's growing energy needs at a time when the world is battling with the negative impacts of CO_2 emissions resulting from the burning of fossil fuels for energy generation.

The decisions that will follow concerning the development of the region's energy sector will thus have long-term implications for individual welfare, national economic development, and CO_2

emissions because investment in energy infrastructure spans several decades. Given recent technological advancements and cost reductions, the large-scale deployment of renewable energy offers Sub-Saharan African countries a sustainable, cost-effective path to rapidly provide affordable energy to its huge population that has been deprived of modern energy as well support its growing economies.

Tanzania, the case in study depends on biomass for the provision of 84% of its total primary energy needs and has an average electricity consumption per capita of 108kWh per year, compared to Sub-Saharan Africa's average consumption of 550kWh per year and less than half of the consumption of low-income countries (IRENA, 2014). The country's electricity generation mix is currently dominated by natural gas and hydropower. The dependence on hydro power has created supply security problems both historically and in recent years with frequent seasons of drought. Large hydropower as a share of total capacity declined by nearly two-thirds between 2002 and 2006 (from 98% to 45%), and now stands at just under 40% of available electricity generating capacity (African Development Bank Group, 2015). The country therefore needs to diversify its energy mix by increasing its commitment in developing its other renewable resources (solar, wind and geothermal) in-order to reduce CO_2 emissions from energy generation and avoid over reliance on hydropower.

1.2 Energy Planning: 'A Necessary Pre-requisite for RE Adoption'

It is without doubt that the adoption of renewable energy provides the most plausible solution to the mentioned challenges of affordable modern energy access, climate change and the unprecedented rise in energy demand due to high urbanization and population growth rates. However, it is necessary to spend time on planning the integration of renewable energy before introducing changes in order to ensure the sustained penetration of renewables in the current energy systems (Grubler, 2013). Energy system models assist us to understand the impact of making changes to the energy system before we make them (SETIS, 2016). This attribute of energy models makes them a vital tool for energy planning as they allow planners and policy makers to create a clear picture of the energy system and helps them understand the implications of their proposed plans thus giving them the ability to make informed decisions. Energy planning for a geographical area provides a method of re-organizing and redirecting money already allocated for the supply of energy so that it can be spent more efficient in the future (TransPlan, 2010). An energy plan, when compared to the present situation, will be more efficient if it improves the welfare in the chosen geographical area.

1.3 Motivation

The main motivation for this study stems from the acknowledgement that there is a need for energy modelling tools that could serve as a means to close the gap between a contextual approach to energy systems and the available conventional modeling tools. (Karas, 2004) defines successful energy models as those in which modelers also account for the contexts and dynamic behavior of the energy systems. The numerous conventional modelling and optimization tools, that have been employed for planning renewable energy integration (largely bottom up approaches) model and optimize energy production costs but do not account for all externalities and contexts of a particular energy system and how these contexts and externalities relate and change with time. This study proposes an approach that incorporates social, economic, political, technical and environmental factors and considers their non- liner relationship and dynamic changes with time in the modeling exercise in-order to develop a tool that is relevant to decision makers and investors which can be used for the purposes of fostering growth of renewable energy generation.

In addition, energy models were historically designed to cater to the scope and characteristics of the developed and industrialized world (Bhattacharyya & Timilsina, 2010). However, developing countries and in particular Sub-Saharan African countries have a number of distinct characteristics which make the modelling exercise for these countries challenging. Sub-Saharan Africa's energy contexts experience significant levels of poverty, lack of access to modern energy services due to high costs of energy, and a portion of their energy system is often dominated by informal activities (Tait, Mccall, & Stone, 2014), so renewable energy integration does not only serve the purpose of replacing fossil fuels to reduce emissions but rather, it is critical in ensuring the reduction of the population without access to modern energy. This study therefore is mindful of the Sub-Saharan Africa's energy context in the model development.

1.4 Hypotheses & Research Questions

The study tests the following hypotheses

- A System Dynamics (SD) approach can be successfully applied to planning of renewable energy integration in Tanzania
- Increased commitments to developing RE infrastructure in Tanzania's energy system can help the country to deliver energy at an affordable price and thus reduce the proportion of the population without access to modern energy

The associated questions for the study include:

- What are the key variables that need to be considered when preparing the system dynamics model and how do these variables relate to each other?

- What are the expected energy price values of electricity generating technologies under consideration and how does change in these prices throughout the modelling period affect demand for that particular technology?

1.5 Research Objectives

The following objectives have been set to answer the research questions and test the research hypotheses.

- To identify the system variables that will be used for developing the system dynamics model
- To prepare a causal feedback loop analysis which will define the relationship between system variables, the direction of variable action and the structure of the energy system.
- To construct the system dynamic model on Vensim Software
- To use the model to determine the energy price ratios of the electricity generating technologies under consideration and show how these ratios affect the demand for each technology.
- To investigate how different levels of commitment by Tanzanian authorities in promoting a certain generating technology affects system variables, in particular; energy price and demand.

1.6 Study Purpose and Overview

The purpose of this study is to develop a comprehensive system dynamic model that can be effectively used to analyze the dynamic behavior of energy systems and thus allow informed decisions to be made for renewable energy integration in energy systems. Recognizing that available energy modelling tools for renewable energy (RE) integration are too prescriptive in that they follow pre-defined paths and rules which create some degree of rigidness to the modelling exercise as some important details can be beyond the scope of the models, this research proposes an approach that extends and advances existing RE integration tools by taking into account the dynamic complexities (system uncertainties, nonlinear relationships between system variables and time lags) embedded in energy systems (Mutingi, Mbohwa, & Kommula, 2017) and facilitates the investigation and understanding of feedbacks existing between energy, the society, economy and environment. The study will apply a System Dynamics (SD) approach to develop a model on

Vensim Software that is used to determine energy price ratios and show the resultant behavioral response by demand to energy price ratio changes. The processes of SD approach are divided into two parts, i.e., causal feedback loops and SD model construction. The causal feedback loops are used to identify the relationships between related system variables and the causality in the system of concern (Trappey, Trappey, Lin, & Chang, 2011). Afterward, the SD model is constructed to simulate the dynamic system variation in Tanzania's energy system. Different scenarios in which varying commitment levels to promoting each generating technology by Tanzanian authorities are also simulated to evidently show the benefits of directing more efforts towards renewable energy integration.

1.7 Relevance of Study

The results of the proposed methodology can be used to support decision makers and investors to evaluate benefits of renewable energy integration especially in increasing energy access and enable governments to implement tailor made renewable energy policies and commitments for their particular countries. While conventional optimization models of energy systems can be parameterized to represent any regional or national energy sector to optimize the cost of energy supply, they do not put energy issues into a context (Bassi, 2009). As a result, the models quickly lose relevance as they cannot cope with the dynamic changes within the energy systems and some energy plans have to be constantly reviewed while others have to be abandoned halfway through thus affecting the confidence of decision makers and investors in renewable energy integration. Furthermore, the reluctance to prioritize and invest in renewable energy will slow down the uptake of renewable energy thereby posing serious threats to energy security and sustainability. The system dynamics approach proposed in this study will allow creation of a more robust roadmap to renewable energy integration by outlining the dynamic variations in energy systems and giving an insight on the impacts of actions under future uncertainties.

2 LITERATURE REVIEW

The chapter provides a comprehensive review of literature on energy systems and the planning of energy systems with a focus on renewable energy integration. The review presents different levels of energy planning as well as the various methodologies applied for planning. More insight is given on the use of energy modelling as a methodology for energy planning and an emphasis on system dynamics modelling is provided. A review of previous work done using the system dynamics modelling approach for renewable energy integration in energy systems conclude the chapter.

2.1 Energy Systems

An energy system is a system that is primarily designed to supply energy to end-users. It can be thought of as a network consisting of production from energy sources, storage, transmission, distribution, and consumption of energy (Andersen, 2015). The energy system has been described in various ways with regards to different areas and fields. According to (Bruckner, 1995), the energy economics field, is composed of energy markets and treats an energy system as a techno-economic system that satisfies consumer demand for energy in the forms of heat, fuels and electricity. Energy demand on the other hand, is a quantity that fluctuates subject to various influences which may or may not be techno-economical and include consumer preferences, population growth, prices, and regulations. (Hoffman & Wood, 1999) provide a much broader view and they describe an energy system as a system that consists of an integrated set of technical and economic activities operating within a complex societal framework which uses energy to enhance its standards of living. Energy systems can range in scope, from local, municipal, regional, national, to global, depending on issues under investigation. Figure 2.1 represents the physical components of a generic energy system supplying fuels, heat and electricity to end-users. As represented by (Hake, 2017),energy systems compose of primary energy, conversion and transport then finally consumption.

2.1.1 Primary energy

The primary energy refers to energy that has not been subjected to any conversion or transformation. Primary energy is contained in raw fuels and includes nonrenewable (natural gas, coal, oil), renewable energy (solar, hydro, geothermal, biomass or wind)

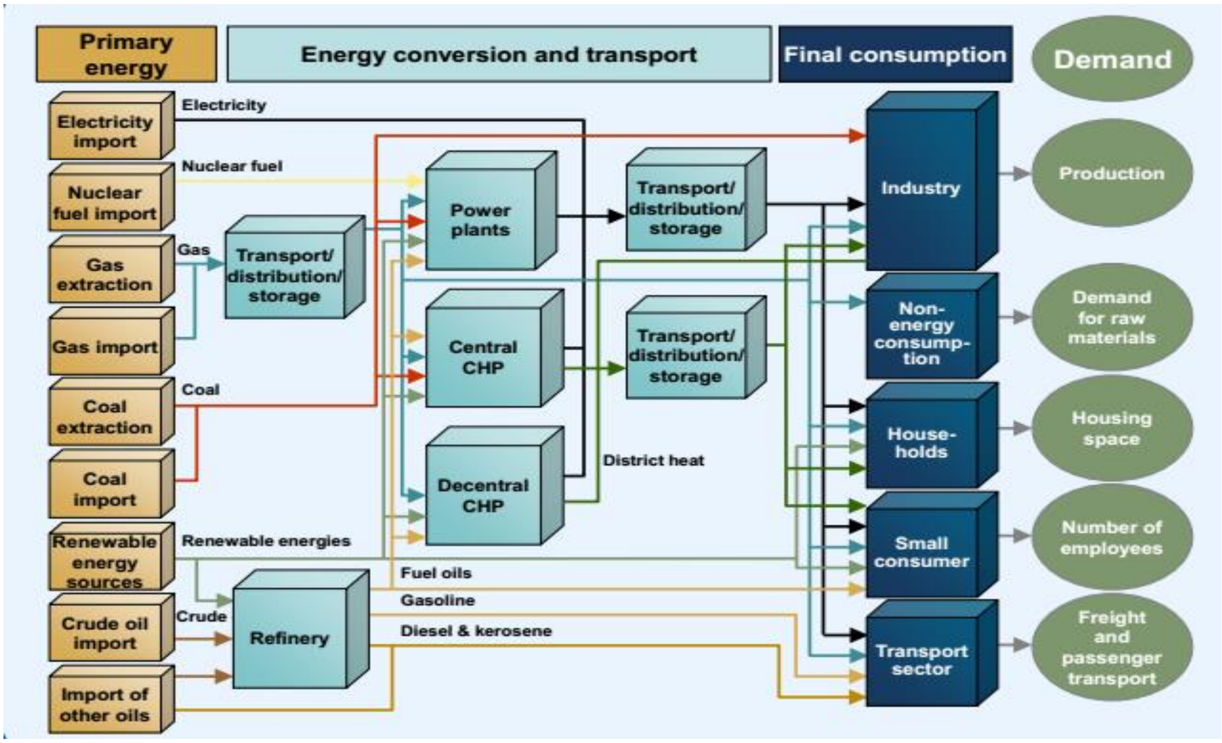


Figure 2.1: Energy System

Source (Hake, 2017)

2.1.2 Energy conversion and transport

The energy conversion and transport processes are used to convert the naturally existing primary energy resources with the use of power plants, co-generation units, collectors, turbines, boilers, furnaces, and refineries into usable (electricity and heat) or semi-usable energy (refined fuels) for domestic, industrial, and transport purposes. The large-scale technologies are generally adopted both for centralized electricity generation and for industrial power and process steam production whereas small-scale technologies largely dominate distributed electricity production by local renewable exploitation and domestic thermal/electric energy production. The energy system also includes energy imports which can be obtained directly as electricity or as fuel that is processed and converted within the energy system boundary.

2.1.3 End use

The end-use subsystem defines a set of energy demand disaggregated in electric power, industrial process steam, domestic heat and other needs (coal for blast furnace, natural gas for cooking systems, petrol and diesel oil for means of transportation, etc.). The amount of energy used for a unit of production (i.e. kilowatt hour (kWh) per ton or kWh per dollar of output) or the amount of energy utilized per unit of service to satisfy household needs (e.g. kWh per lumens of light) depends upon the technology adopted by the end-user of energy.

The concept of energy systems continues to evolve as new regulations, technologies, and practices are developed in-order to meet the exponential energy demand (under the constraints of climate change and resource depletion) for example, emission policies, the development of smart grids, higher integration of renewables and the greater use of energy demand management.

2.1.4 **Energy Systems and Sustainability**

An energy system which reduces the side effects on the environment to a level within its assimilative capacity, and which raises opportunities for economic and social development, taking a longer-term perspective, forms the basis of the concept of energy sustainability (Neves, 2010). The three dimensions of sustainable development must therefore be fulfilled simultaneously

- *Environmental*: by reducing the side effects caused by the energy supply chain and inefficient energy use: GHG emissions, air pollution and depletion of the natural resources;
- *Economic*: by reducing energy dependence and by enabling the activities that generate business and wealth, e.g. by increasing local business investment in renewable energy and energy efficiency;
- *Social*: by improving human health, creating jobs and involving the citizens in decision-making processes.

2.2 Energy Planning

Several authors have defined energy planning in various ways and a review of the literature reveals emphasis on interesting aspects of energy planning. (Prasad, Bansal, & Raturi, 2014) define energy planning as a roadmap for satisfying energy demand of a nation and is accomplished by taking into consideration various influencing factors such as technology, economy, environment as well as the society that impacts the national energy issues. (Thery & Zarate, 2009) suggest that energy planning determines the optimum combination of energy sources to satisfy a given demand. This is done by taking into consideration the multicriteria for decision making, which are, quantitative (economic and technical criterion) and qualitative (environmental impact and social criterion). According to

(Cormio et al., 2003), the basis for energy planning is to satisfy the forecasted energy demand over a given time period by taking into account political, social and environmental considerations, as well as historical data collected for previous energy plans for the location under consideration. (Hiremath, Shikha, & Ravindranath, 2007) indicate that energy planning involves finding a set of sources and conversion devices so as to meet the energy requirements/demand of all tasks in an optimal manner. The various views presented in the definitions provided by different authors reiterates the fact that energy systems are complex systems that are made up of interlinks between demand, supply, technological progress, a technology's market potential, the environment and the society and good energy planning takes into consideration all of these variables and parameters to ensure sustainable development. As such; an energy plan or roadmap must be one of the pillars for a nation's sustainable development agenda.

2.2.1 **Energy planning and policy formulation**

Energy planning facilitates energy policy formulation. As the importance of energy in policy making has become apparent, research and analysis in the field of energy planning has grown rapidly. The field has since evolved from small independent planning groups in major sectors of the energy industry to one in which more stakeholders drawn from government agencies, local utilities, academia and other interested groups are active in the development and execution of energy plans (Hoffman & Wood, 1999). A lack of planning can lead to serious problems for an industry or country. Energy planning makes important contributions to the knowledge base for better energy policy making and good decisions are always based on robust research findings. Therefore; a good energy plan should always be based on sound research of the energy demand and consumption, energy prices, supply technologies, population growth, environment and social impacts, success of an energy harnessing technology and influence of political situation in a country. Once formulated and adopted, any energy policy must be adaptive and must also evolve as conditions and objectives change.

2.2.2 **Objectives of planning energy systems**

If problems caused by energy consumption and solutions to these problems appear obvious (for instance replacing fossil fuels with renewables to reduce emissions or increasing capacity to meet demand), it may seem unnecessary to spend time on planning before introducing these changes. However, calculation of potentials of different solutions, comparison of technologies, identification of barriers to change; ensure more sustainable solutions to energy problems. Energy planning for a geographical area provides a method of re-organizing and redirecting money already allocated for the supply of energy so that it can be spent more efficient in the future (TransPlan, 2010). An energy plan, when compared to the present situation, will be more efficient if it improves the welfare in the chosen geographical area.

The typical focus of energy plans includes but is not limited to;

- renewable energy integration
- energy resource allocation
- demand-side management
- energy efficiency
- building energy management
- transport energy management and electric utility planning

Figure 2.2 illustrates an example of an energy supply planning process with renewable energy integration and several factors that come into play during the planning process.

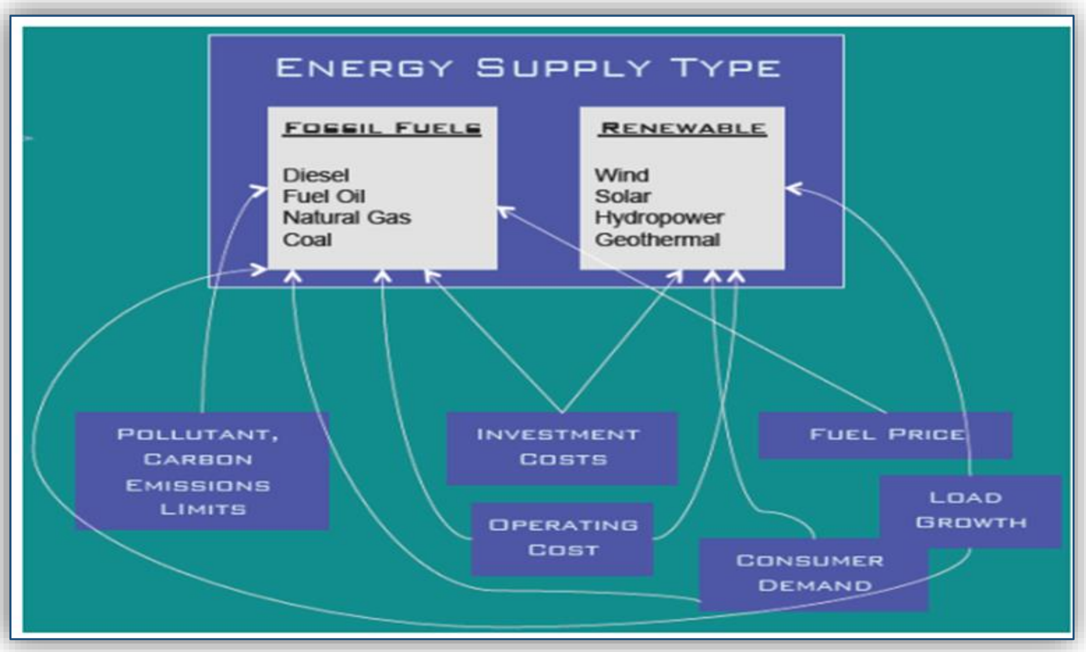


Figure 2.2: Energy Supply Planning Process

Source: (Hawkes, 2015)

The fundamental rationale behind energy planning seeks to:

- **Provide cheaper energy services** in-order to make more money available for consumption. This can be achieved through minimizing total system costs which leads to a reduction in total consumer bills.
- **Create employment:** New local work places can be generated since employment is often required in the local production of energy saving equipment, energy conversion technologies, energy producing equipment and renewable energy technologies as well as in the supply of regional fuels (replacing imported fuels). Using a local labor force and local fuels means that money for energy will stay within the area and within local business.
- **Reduce environmental problems**; thus, reducing health problems and the catastrophic effects of climate change
- **Reduce dependency on imported fuels and energy services**; this may reduce debt to other regions and thus open new possibilities for the area to make its own decisions.
- **Enhance reliability of energy services**
- **Ensure security of energy resources supply**

Some of the questions asked during the energy planning process may include

- What technologies or policies help meet the development of the energy sector in a techno-economic and socio-economic manner?
- What kind of investments need to take place, when, and at what level of operation?

This is then iterated in more detail as more information and data is required to develop targets and policies (Howells, 2013). A solid and realistic energy plan can only be developed if local problems, objectives and resources have to be taken into account throughout the whole planning process.

2.2.4 Energy planning levels

(Hoffman & Wood, 1999) and (Thery & Zarate, 2009) provide a useful classification of modes and levels of planning. They define three levels of planning which include: operational, tactical and strategic planning

2.2.2.1 Operational level

The **operational level** aims to plan on a short- term (hours, days, months, till the year) perspective the energy production for a conversion or energy generating unit evaluating its optimal operating parameters. Each conversion unit is distinguishable from each other by its production capacity, its efficiency then the distance between itself and the end use consumer. The size of time horizons determines the nature of the data that is used as well as the actions to be implemented at each level. (Cormio et al., 2003). For instance, the short-term forecasting of future energy demand will be based on the analysis of historical data and extrapolating load curves under different influences like climate change, variation of energy price and consumer behavior. The aim of the short-term energy planning exercise is to ensure reliability of energy services required by exploiting the reactivity of existing energy systems.

2.2.2.2 Tactical level

The **tactical level** aims to establish energy planning for a cluster on a medium term (from 1 year to 10 years). A cluster is defined as a set of several energy producers and a set of consumers (individuals, local authorities, enterprises) associated in order to share their energy production equipment. Each cluster presents its own energy demand, its own production system, its geographical constraints and natural resources. In the medium term, the planning exercise is based on demographic evolution, socio-economic changes and technical progress. The action at this level of planning continues to ensure reliability of the existing system, however within a longer time horizon and considers the possibility of development of new energy infrastructure

2.2.2.3 Strategic level

The **strategic level** aims to establish energy planning on a long-term point of view, on a territorial scale. With available data on the estimation of the demand evolution for the delivered energy from several decades, this level allows one to determine the evolution of energy quantity to produce for each period (year, decade depending of the temporal scale studied). In the long-term, technological advancements, political constraints, social and environmental requirements are considered to have significant impact on the planning. It is necessary at this level to include the likely disruption of some primary energy resources for example resource depletion and depletion of high technical potential sites. The long-term energy planning actions involve development of new energy infrastructure as well as promoting or restricting given technologies. A typical example would be promoting renewable energy use and minimizing the use of fossils. This level is based on the evaluation of different energy scenarios. The scenario analysis is used to cater for risks and uncertainties at this level that maybe detrimental to energy planning (Prasad et al., 2014).

The geographical dimension also dictates the level of energy planning. (Hiremath et al., 2007) suggest the following levels:

- **Global level**: overall energy system of a nation or continent.
- **regional level**: concerns the energy system of a city or an entire city (also called cluster) intending to share their resources and equipment dedicated to energy conversion.
- **local level:** concerns the study of an energy conversion unit.

Figure 2.3 illustrates the planning levels on a spatial- temporal scale

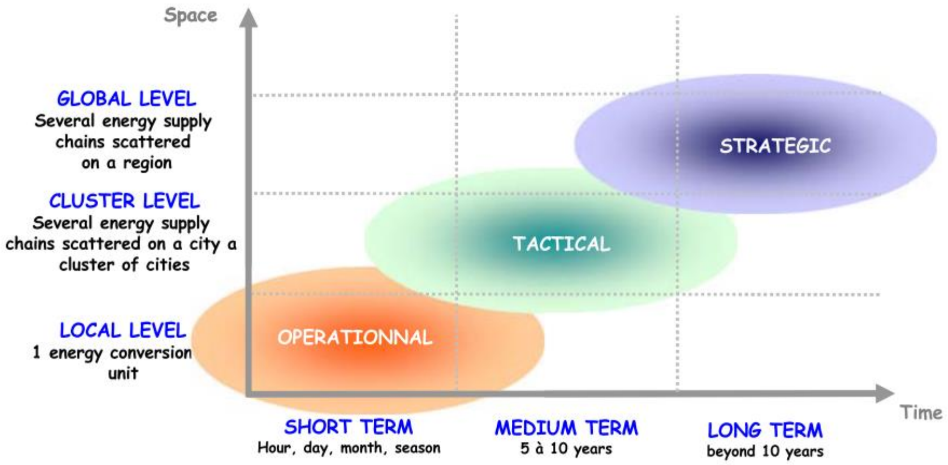


Figure 2.3: Energy Planning Levels on a Spatial -Temporal Scale

Source: (Thery & Zarate, 2009)

2.3 Methods for Energy Planning

(Cormio et al., 2003) classifies energy planning methods into three categories; planning by *Inquiry, Analogy* and *Models.* (Terrados, Almonacid, & Hontoria, 2007) also describe 2 techniques of energy planning; *Delphi Techniques* and *Territorial and Rural Planning.* (Prasad et al., 2014*)* identify 2 methods which can be used, planning by *Models* and by *Inquiry.* According to (Prasad et al., 2014*)*, the Delphi technique is a methodology that falls under planning by *Inquiry*. Planning by *Models,* however is a common methodology from most literature and a closer look at the methodologies shows that they tend to overlap. This section will give a brief description of energy planning methodologies reviewed from literature.

2.3.1 Inquiry methodology

This method is used for determining the potential of energy technologies which are currently in research phase to be included in the long-term energy planning. Logical reasoning is made on whether new technologies in their initial development stages can contribute significantly in the future or whether new technologies in the advanced development stages are competitive enough with other technologies. A subset of the inquiry methodology includes technological progress and Delphi method (Prasad et al., 2014).

2.3.1.1 Technological progress

Technological Progress utilizes experience curves for introducing new technologies in long term planning. Experience curves exploited to set targets and to design measures to make new technologies commercial. They provide powerful tools for formulating low-cost strategies to reduce and stabilize CO_2 emissions in the long term (IEA, 2000).

2.3.1.2 Delphi method

A Delphi survey is a series of questionnaires that allow experts or people with specific knowledge to develop ideas about potential future developments around an issue (Prasad et al., 2014). The characteristics of Delphi technique are anonymity, iteration of series of questions (where once consensus is reached on a question it is omitted from succeeding iteration), controlled feedback and statistical group response. (Terrados et al., 2007) combined the Delphi Technique and SWOT analysis for multi-criteria decision-making analysis in energy planning.

2.3.2 Territorial and rural energy planning methods

Participatory approaches for energy planning implementation have been extensively used in rural areas and developing countries. In a study done by (Neudoer, Malhotra, & Ramana, 2001) they showed that programmes launched for rural energy development planning in India had little success due to the absence of mechanisms to assure how final users were affected. In their work, they develop planning methodologies and tools to facilitate public participation in energy planning.

2.3.3 Analogy planning methods

According to (Cormio et al., 2003), the planning by analogy methodology allows the simulation of the same quantity, with a time lag, in a less developed country, through the use of a leading case as reference and the knowledge of the time behavior of a quantity in a more developed country. The 'analogue' approach is often used to check and compare outputs produced by other methods.

2.3.4 Planning by Energy Models

Energy system models are developed and applied in a wide variety of energy planning and policy making activities and they provide support at all three planning levels (Hoffman & Wood, 1999). Energy modeling involves building computer models of energy systems for the purposes of analyzing the energy systems. The energy models are used to project future energy demand and supply of a country or a region. They are mostly used in an exploratory manner assuming certain developments of boundary conditions such as the development of economic activities, demographic development, or energy prices on world markets. They are also used to simulate policy and technology choices that may influence future energy demand and supply, and hence investments in energy systems. (Herbst, Toro, Reitze, & Jochem, 2012). Energy models oftenly utilize scenario analysis to investigate the different assumptions about the technical, social or economic conditions under consideration. Model outputs may include system feasibility, carbon emissions, financial costs, natural resource use and energy price of the system under investigation.

Energy system models help us understand the impact of making changes to the energy system before we make them. This attribute of energy models makes them a useful tool for energy planning as they allow the planners to make decisions with a clear picture of the implications of their proposed plans. Energy systems are employed for both normative or descriptive analysis and predictive purposes. In normative analysis the primary objective is to measure the impact on the system of changing some element or process that is an exogenous, or independent, event in the model. Predictive models are used to forecast energy supply and/or demand and attendant effects over a particular time horizon. According to (Hoffman & Wood, 1999), Most models have both normative and predictive capability and a partition of models into these classes can be misleading.

With a model we make an abstraction of the real world and be able to plan something. Every modelling approach abstracts to a certain degree from reality using stylized facts, statistical average figures, past trends as well as other assumptions. Therefore, energy models represent a more or less simplified picture of the real energy system and the real economy; at best they provide a good approximation of today’s reality (Howells, 2013)

Figure 2.4 shows a typical example of a modelling process for an energy investment plan with renewable energy integration.

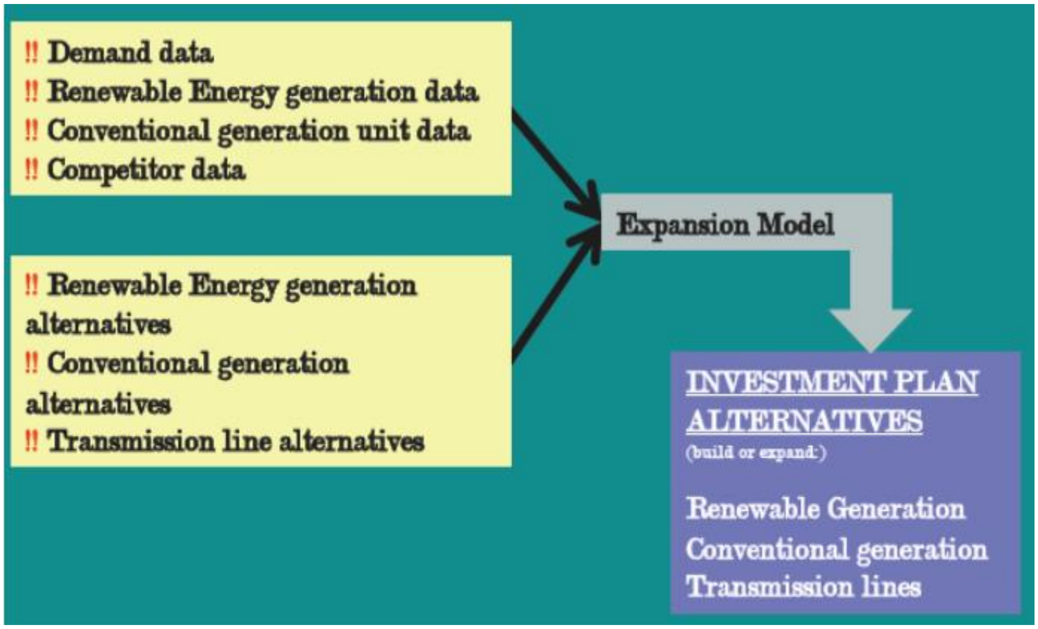


Figure 2.4: Energy Investment Plan Model

Source: (Hawkes, 2015)

A typical “energy systems planning model”:

- Will relate techno- physical aspects of the energy system such as type of energy technology (e.g. Gas GGCT vs Wind) required, the extent of that installation (MWs) required, when the installation operates, its level of activity etc. to attributes such as: cost, environmental or economic impact, flexibility, robustness
- It may include some level of feedback between the two.
- And this may (and may not) be to meet some objective subject to various constraints

2.4 Classification of Energy Models

All energy models share general characteristics, for example, any model will always be a simplification of reality and only includes the aspects that the model developer deemed important at that point in time. However, there are also distinct characteristics that energy models possess which necessitates their classification. Several authors have classified energy models in various ways. In their review of decentralized energy planning models, (Hiremath et al., 2007) highlighted the fact that the problem with classifying energy models is that there are many ways of characterizing the different models, and there are only few models, if any, that fit into one distinct category. Table 2.1 summarizes the classification of energy models from literature.

Table 2.1: Classification of Models from Literature

Author	Classification Criteria
(Hiremath et al., 2007)	• General and specific purposes of energy models • The model structure: internal assumptions and external assumptions • The analytical approach: top-down vs. bottom-up • The underlying methodology • The mathematical approach • Geographical coverage: global, regional, national, local or project • Sectoral coverage • The time horizon: short, medium, and long term
(Prasad et al., 2014)	• methodology (econometric, simulation and optimization) • approach (top-down, bottom-up)
(Cormio et al., 2003)	• econometric models and optimization models
(Nakata, Silva, & Rodionov, 2011)	• modelling approach (top-down and bottom-up) • methodology (partial equilibrium, general equilibrium or hybrid) • modelling technology (optimization, econometric or accounting) • the spatial dimension (national, regional and global)
(Herbst et al., 2012)	• Intended use: (data analysis, ex post evaluation, forecasting, simulation, optimization, estimation of parameters, etc.), • regional coverage (regional, national, multinational), • conceptual framework (top-down vs bottom-up • information available (data on final energy, useful energy, energy demand by branches in the service, transport, or industrial sector)
(Bhattacharyya & Timilsina, 2010)	• sectoral coverage, • time horizon • spatial focus.
(Hoffman & Wood, 1999)	• linear programming-based method • input-output approach • econometric method • process models • system dynamics and game theory

The classification of models using the Top down, Bottom Up criteria, explicitly describes the energy models and a closer look reveals that most of the classification criteria are embeeded in this classification criteria.

2.4.1 Bottom-up energy models

The **bottom-up models** utilize an engineering approach to develop energy models with thorough descriptions of technologic aspects of the energy system and how it can develop in the future. The main characteristic of a conventional bottom-up energy model is its relatively high degree of technological detail (compared to top-down energy models) used to assess future energy demand and supply. Energy demand is typically provided exogenously, and the models analyze how the given energy demand should be fulfilled in a cost-optimal fashion (Helgesen, 2013). Their technological detail and transparency considering technological progress and the diffusion of new energy technologies make bottom-up energy models unsuitable for very long-term energy demand and supply projections in technology areas with re-investment cycles of less than 20 years for instance, future generations of a new technology may be quite different from its present type. Bottom-up models would ask questions like:

- How can a given emission-reduction task be accomplished at minimum cost?

Table 2.2 summarizes bottom up energy models (Helgesen, 2013), (Herbst et al., 2012), (Frei, 2003)

Table 2.2: Bottom-up energy models

Model	Methodology	Examples
Optimization	Optimize the choice of technology alternatives with regard to total system costs to find the least-cost path and can also be categorized as partial equilibrium models, since they balance demand and supply in the covered sectors.	ENERGYPLAN, IKARUS MESSAGE, PRIMES, HOMER, WASP TIMES/MARKAL
Simulation	Simulate the behavior of consumers and producers under various signals (prices, income, policies) which may not be optimal behavior. Their modelling aspects depart from the pure optimization framework and they make use of scenario analysis	ENPEP, INFORSE, LEAP, MESAP, PLANET, POLES, REEP, WEM, RETScreen, WIEN
Accounting	Less dynamic, and do not consider energy prices. These models mainly apply exogenous assumptions on the technical development.	MAED MED-PRO MURE
Multi- Agent	Simulation approach which considers market imperfections such as strategic behavior, asymmetric information and other non-economic influences.	LIBEMOD, MULTIMOD

2.4.1 **Top-down energy models**

The **top down models** are built using an economic approach. The models describe the whole economy and emphasize the possibilities to substitute different production factors in order to optimize social welfare. These models do not include many technical aspects. The interplay between energy and other production factors to create economic growth is captured in production functions, and opportunities to make changes in fuel mixes are described by elasticities of substitution. Driven by economic growth, inter-industrial structural change, demographic development, and price trends, top down models try to equilibrate markets by maximizing consumer welfare using various production factors (labor, capital, etc.) and applying feedback loops between welfare, employment, and economic growth. (Herbst et al., 2012). Top-down models would ask the question:

- By how much does a given energy price movement change energy demand or energy-related carbon emissions?

Table 2.3 summarizes top down energy models (Guanghong Zhou, 2015), (Frei, 2003), (Herbst et al., 2012), (Helgesen, 2013)

Table 2.3 Top- Down Energy Models

Model	**Methodology**
Input- Output	Follow the monetary flows between different sectors of the economy and include both intermediate and end-use deliveries from each sector. From these interrelations one can estimate monetary effects of economic shocks or structural changes in the economy. These models are not dynamic in prices, and assume that prices are given exogenously
Econometric	Deal with time series analysis and estimate statistical relations between economic variables over time in order to calculate projections from the resulting model
Computable General Equilibrium	Assume that all markets are in perfect equilibrium to start with (no excess demand or supply, no obstacles to profitable potentials of energy efficiency) and after intervention, (e.g. introduction of special taxes or subsidies, etc.), the equilibrium is preserved by price adjustments which cannot be influenced by the involved agents (e.g. households, firms, and government)
System Dynamics	It involves simultaneous linear and nonlinear equations which are used to represent functional and feedback relationships between parameters of the energy system.

One major advantage of top-down energy models is their application of feed-back loops to welfare, employment, and economic growth. This endogenous assessment of economic and societal effects results in higher consistency and facilitates a comprehensive understanding of the impacts of changing the energy system during energy planning on the economy of a country or region.

2.5 System Dynamics Modelling

Systems thinking is a process of understanding how things as parts of a set influence each other. It is an approach for problem solving by viewing ‘‘problems’’ as parts of an overall system rather than reacting to a specific part. In his publication; “Systems Thinking for a Complex World”, (Sterman, 2000), emphasizes the inevitable need to apply system thinking in solving today’s problems. His opening remarks in the preface of his book are insightful:

> “Accelerating economic, technological, social, and environmental change challenge managers and policy makers to learn at increasing rates, while at the same time the complexity of the systems in which we live is growing. Many of the problems we now face arise as unanticipated side effects of our own past actions. All too often the policies we implement to solve important problems fail, make the problem worse, or create new problems. Effective decision making and learning in a world of growing dynamic complexity requires us to become systems thinkers-to expand the boundaries of our mental models and develop tools to understand how the structure of complex systems creates their behavior”

(Qudrat-Ullah, 2016) highlights the fact that energy systems are feedback systems and thus system dynamics methodology appears to be a natural choice for the energy policy modeling community. (Mutingi et al., 2017) identify and outline dynamic complexities of energy systems which warrant the application of the system dynamics approach when solving and handling issues that pertain to energy systems. The following section briefly describes the dynamic complexities while illustrating the characteristics of the system dynamic approach

2.5.1 Causal relationships of system variables

System variables have causal influence between them (e.g. influence of supply energy mix on energy resources, price, environment e.tc) and it is imperative to understand these causal influences when planning energy systems. The system dynamics approach adequately addresses these causal interlinkages making them suitable for energy planning purposes. Causal relationships can be

- *Positive*: the positive sign at the head of the arrow shown in Fig 2.5 means that if the variable at the tail is increased, so will be the variable at the head; if the variable at the tail is decreased, the variable at the head will also decrease that is changes in the variables are in the same direction (an increase in energy demand warrants an increase in the supply, and a decrease would also result in a decrease of energy supply) or

- *Negative* the negative sign at the head of the arrow shown in Fig 2.6 means that if the variable at the tail changes, the variable at the head will change in the opposite direction (More energy conservation reduces energy demand

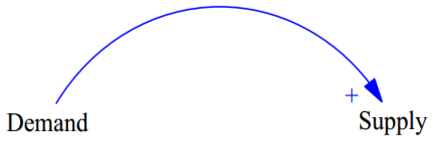


Figure 2.5: Positive Causal Effect

Figure 2.6: Negative Causal Effect

2.5.2 Time lags / Delays

There are several time delays between actions and their consequences among variables of any energy system. Taking the demand supply cause-effect relationship, if the demand for electricity increases, it only after some delay (e.g., due to the construction of new power plants to meet the additional demand), the increase of supply of electricity can be realized. (Qudrat-Ullah, 2016). Delays can be in the form material (movement of fuels to power plant) or information (time for approval of projects). These delays can have significant impact on project investors, shareholders, as well as energy policy makers and planners concerned with energy supply. System dynamics approach accounts for such delays and are represented by having a symbol on the arrow that links the two variables as show Fig 2.7

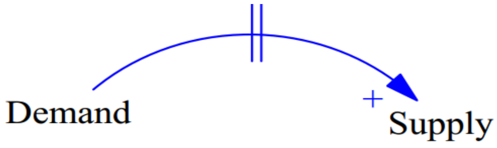


Figure 2.7: Time lag

2.5.3 Feedback structures

The observed trends in carbon emissions, adoption of renewable energy technologies, energy prices, and energy consumption are a result of underlying feedback structures in the energy systems (Mutingi et al., 2017) and system dynamics approaches address this feedback mechanism behavior of energy systems through the construction of feedback loops A feedback loop is a closed sequence of various cause–effect relationships(Qudrat-Ullah, 2016). A feedback loop can be either a Balancing Loop represented by the letter B inside the loop from Fig 2.9 or Reinforcing Loop represented by the letter R in Fig 2.8

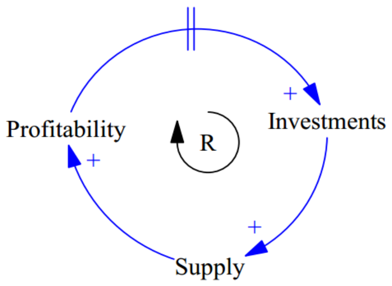


Figure 2.8: Reinforcing Loop

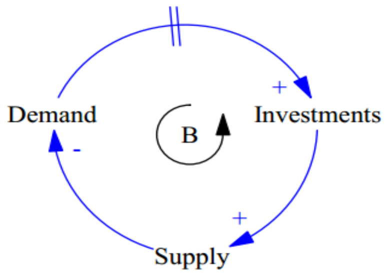


Figure 2.9: Balancing Loop

2.5.3.1 Balancing/ Negative/ Self-Correcting Feedback loops

Such loops are circles of cause and effect that counter a change with a push in the opposite direction. The harder the push, the harder the system pushes back (Sterman, 2000). From the figures adopted from (Qudrat-Ullah, 2016),an increased demand leads to increased investments in the electricity generation technologies. In turn, increased investments, after a delay, cause an increase in the supply of electricity. The increased supply then will close or reduce the gap between demand and supply or result in a decreased demand of electricity. For this loop, any change in the demanded is met with an opposing action

2.5.3.2 Reinforcing / Positive Feed Back Loops

These are loops in which an action produces a result which influences more of the same action thus resulting in growth or decline. From the positive feedback loop in Fig 2.8, increasing the supply of electricity by the utility, improves its profitability. The increased profits will cause more investments, thus improving its profitability even more resulting in a growth-propelling loop.

(Sterman, 2000) provides a methodology of determining the polarity of feedback loops by considering the negative signs in the loop. If the feedback loop has zero or an even number of negative signs it is a Reinforcing Loop and if it has an odd number of negative signs then it is a balancing loop.

Combining Fig 2.8 and Fig 2.9 results in Fig 2.10 which is referred to as the Causal Loop Diagram (CLD), a diagram that represents all the feedback loop diagrams of an energy system.

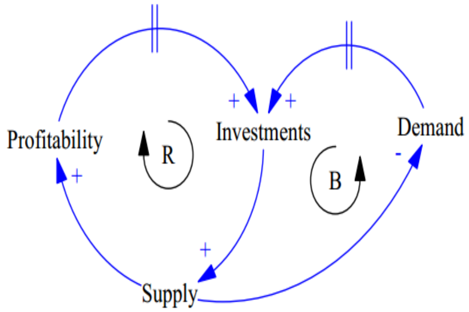


Figure 2.10: Causal Loop Diagram (CLD)

2.5.4 System uncertainties:

Energy sectors are often faced with unprecedented changes in demand, investments and energy usage which leads to unforeseen dynamic imbalances in the energy system. Major sources of uncertainties stem from various influences from incentives, technological developments, price fluctuation and unpredictable human behavior.

2.5.5 Nonlinear relationships between system variables

In energy systems, dynamic complexity arises from the fact that the response (or effect) of the system to an action (or cause) is often non-linear. The response of the system to the action depends on its current state. As such, these non-linear relationships between system variables cannot be analyzed using conventional econometric and mathematical programming models.

2.5.6 Stocks and Flows in System Dynamic Modelling

Stocks and flows, along with feedback, are the two central concepts of dynamic systems theory. Stocks are accumulations. According to (Reddi, Li, Wang, & Moon, 2013), a ‘stock’ is analogous to a bathtub, and the ‘flows’ are analogous to the inlet and outlet of the bathtub. Stocks are connected by flows that regulate the accumulation of modelled system variables. The system variables define the values assumed by the flows and thus implement the system logic. During each simulation run, the difference between the inlet and outlet accumulates in the stock. At any point of time, the levels of all the stocks represent the state of the system and generate the information upon which decisions and actions are based (Sterman, 2000). Fig 2.11 shows the stock and flow representation of the accumulation of generating capacity of an energy system

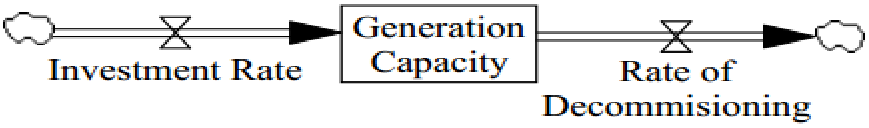


Figure 2.11: Stock and Flow Diagram for Generating Capacity

The generating capacity is a function of the difference between the inflow (Investment rate that causes an increase in the generating capacity) and the outflow (Decommissioning Rate which results in a decrease in the generating capacity) At any time, the level of the generating capacity(stock) influences several decisions on the energy planning process which include increasing or decreasing the energy investments. The mathematical representation of stocks and flows

$$\mathrm{Stock}(t) = \int_{t_0}^{t} [\mathrm{Inflow}(s) - \mathrm{Outflow}(s)]ds + \mathrm{Stock}(t_0)$$

- Stocks are represented by rectangles (suggesting a container holding the contents)
- Inflows are represented by a pipe (arrow) pointing into (adding to) the stock.
- Outflows are represented by pipes pointing out of (subtracting from) the stock.
- Valves control the flows.
- Clouds represent the sources and sinks for the flows A source represents the stock from which a flow originating outside the boundary of the model arises; sinks represent the stocks into which flows leaving the model boundary drain.

2.6 Renewable Energy Integration

Current energy systems heavily rely on traditional fossil fuel-based energy sources such as coal, oil, and gas. However, the increase in global energy demand coupled with depleting fossil energy resources and the environmental problems related to the utilization of these fossil resources (climate change, emissions , land degradation) , raises the need for accelerated actions to be taken towards achieving sustainable energy systems. (Sgouridis & Csala, 2014) highlight that the successful completion of a transition to sustainable energy systems marks the transformation of an economy based on depleting energy stocks to an economy based on renewable energy flows. Therefore, the integration of renewable energy into current energy systems does not become a choice but rather mandatory for the attainment of sustainable energy systems and the planning of energy systems for the penetration of renewable energy cannot be over-emphasized.

2.6.1 **Renewable energy integration approaches**

Literature has principally 2 approaches to the concept of "Integration". In some studies, integration is an energy plan that describes the relationship between renewable electricity supply and the power Alternating Current (AC) systems and renewable thermal energy supply into the thermal systems. The integration is considered in both on -grid or off-grid scenarios and is usually applied at the local or cluster level of planning. On the other hand, some studies consider the concept of integration as an energy plan that describes a relationship between renewable energy generation and the overall energy system with all its dynamics and is normally done at cluster, national or global level. This research focuses on the latter approach in its methodology.

2.6.1.1 Integration of renewables into power or thermal systems

The integrated RE is the process of power transfer "watt" from renewable energy sources to the utility system grid, so the network is fed by a source of RE. The output of power from RE has to be an AC power in order to meet integration conditions, after which it can be distributed.(Alsaif, 2017). The system can also incorporate storage components like battery banks, hydrogen storage tanks or fly wheels to overcome the challenges of intermittencies. A general integrating RE-process system is shown in Fig 2.14. The planning technique majorly focuses on the techno-economic aspects of the energy system where the operation of the physical components of the energy conversion units and their relation with the power and thermal system distribution networks are simulated and optimized. (Alsaif, 2017) notes that this integrating approach is challenging, especially in the large scale of the system, and it has many issues and difficulties that should be achieved in the right way to have the desired connection. He summarizes the challenges in the Figure 2.15. (Mikkola, 2017) finds ways to address some of these challenges in-order to increase flexibility in integrated systems and enable higher shares of Variable Renewable Energy (VRE) in urban systems. The research developed 3 computational models in relation to both electricity and thermal energy in cities of Helsinki in Finland, Concepcion in Chile and Shanghai China. The thesis showed that by viewing the energy systems as a whole instead of focusing on only energy form, the flexibility of the system can be remarkably increased, even without massive investments in traditional network infrastructure.

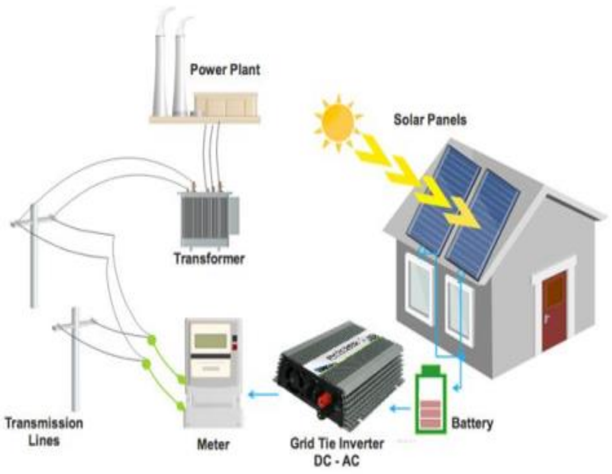


Figure 2.12: General Integration Process

Figure 2.13: Challenges of RE- Grid Integration

Renewables integration in power and thermal systems has also immensely contributed to the emergence of microgrids which are now being extensively applied in both on grid (in areas which are connected to the grid) or decentralized off grid systems. The microgrids can have a share of renewables or can be composed of 100% renewables. In their study, (Plain, Hingray, & Mathy, 2018) account for low solar resource days to size 100% solar microgrids power systems. (Domench, Ranboldo, Ferrer-Marti, Pastor, & Flynn, 2017) design two mathematical models; optimizing lifespan costs and supply quality in the design of isolated electrification projects. (Lopez & Espiritu, 2011) apply the HOMER software to plan hybrid power systems integration considering various renewable energy technologies.

2.6.1.2 Integration of renewables in the overall energy system

This approach encompasses the technical, social, economic, political and environmental aspects of the energy system (technological improvements, demand, energy prices, government plans and policies, population growth, social lifestyle, urbanization etc.) to develop energy plans which are meant to increase the share of renewables in the energy system. The energy planner can consider all aspects or just a few of the energy system and is at liberty to take any direction to describe the integration of renewables in energy systems with the intention to provide useful information to policy and decision makers as well as for the purposes of policy analysis.

(Zeng, Frenchman, & Ferreira, 2011) explores effective ways of combining RE with urban development through the analysis of the relationship between urban form and renewable energy production in Jinan China. (Cormio et al., 2003) propose a bottom-up energy system optimization model to support planning policies for promoting the use of renewable energy sources. (Tait et al., 2014) make use of the LEAP modelling tool to develop sustainable energy plans with high levels of renewable energy integration for Sub-Saharan Africa’s Municipalities. In their study, (Lund & Mathiesen, 2009) used Energy PLAN to develop an energy plan for Denmark with 100% share of renewables. By 2050 and they managed to show that a 100% renewable energy supply based on domestic resources is physically possible.

2.6.2 System Dynamics Renewable Energy Integration Models

The energy sector has extensively used models for planning energy systems with high levels of renewable energy integration. Most energy models address a few of the feedback mechanisms relevant especially for long term energy planning. (Vogstad, 2004) highlights that most of these models involve optimization methods that need simplified mathematical representation and it is for this reason that they usually omit some important feedback mechanisms and such relationships are then left to the decision makers policymakers’ own personal judgement, resulting in controversies. He gives a typical example in which policy makers emphasize short-term effects and long-term effects differently; some can argue that substitution from coal to gas is the more cost-effective environmentally sound policy whereas others argue will argue that renewables might be costly in the short run, but will be more cost-effective in the long run, when the learning curve effect is brought into the equation. The system dynamics approach however, tries to capture the main feedback mechanisms that many a times cause controversies to find efficient policies to support the transition from a fossil fueled towards a renewable based energy supply.

Fig 2.14 is a Causal Loop diagram extracted from a study done by (Aslani, Helo, & Naaranoja, 2014) on the role of policies that support renewable energy integration in reducing energy dependency of the country. Their analysis shows that despite 7% electricity/heat consumption growth by 2020 in Finland, dependency on imported sources will decrease between 1% and 7% with an increase in renewable energy capacity.

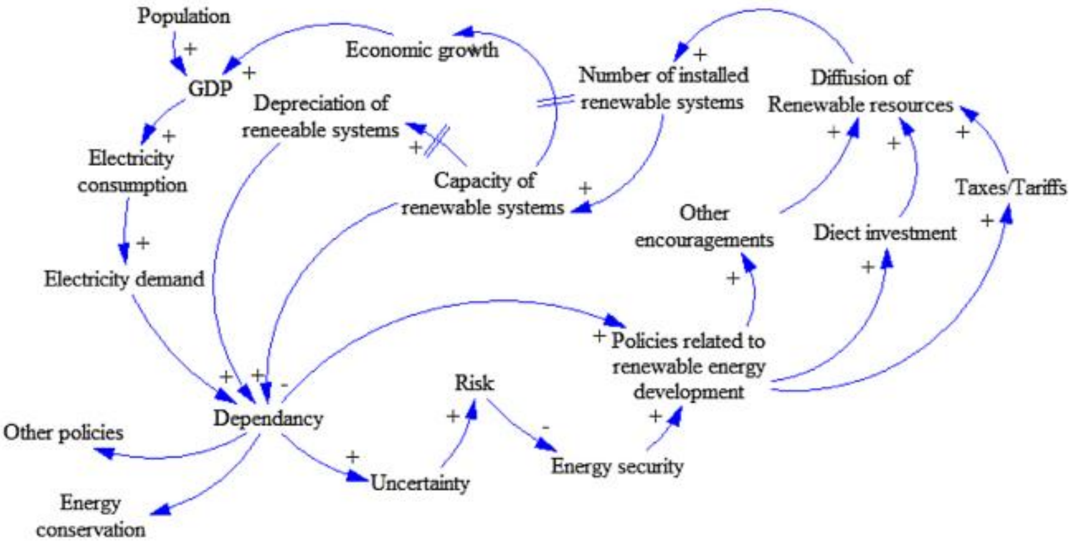


Figure 2.14: Feedback structure on the role of RE policies in energy dependency and security in Finland

Source: (Aslani et al., 2014)

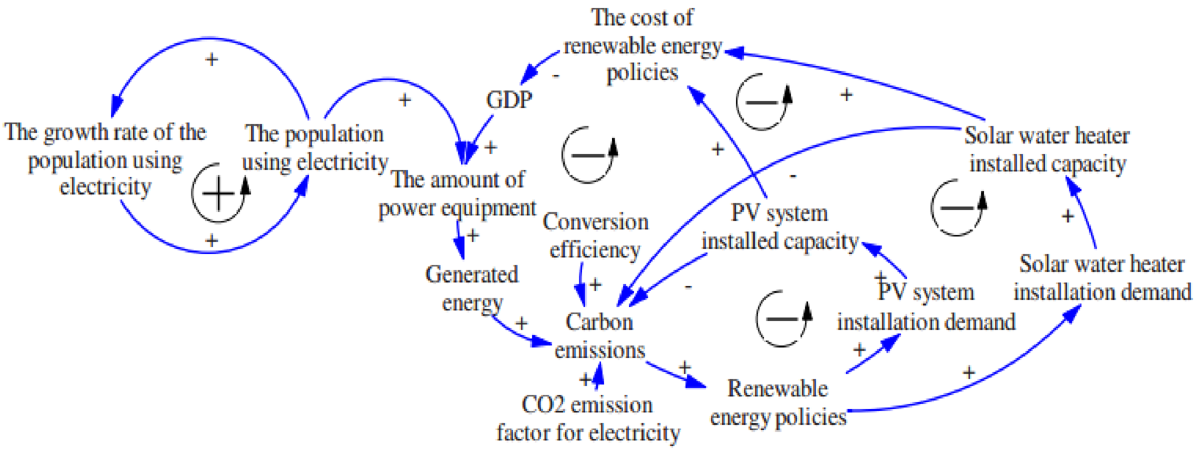


Figure 2.15: The renewable energy policies causal feedback loops

Source: (Trappey et al., 2011)

Table 2.5 gives a summary of some of the previous work done in renewable energy integration using a system dynamics approach that was referred to in this thesis during the construction of the System Dynamics Model

Author	**Objective**	**Results**
(Trappey et al., 2011)	Cost benefit evaluation of the effectiveness of RE policies on promoting solar energy applications in Taiwan	The developed model effectively described the relationship between the renewable policies, the impacts of economy, and the effects of carbon emissions.
(Vogstad, 2004)	System dynamics analysis of the Nordic electricity market in the transition from fossil fuel toward a renewable supply within a liberalized electricity market	The model provided a theory of the development of the Nordic electricity market in response to various energy policies, both in the long and the short term. The reduced investments in renewables in the long run resulted in increased emissions.
(Sgouridis & Csala, 2014)	Framework for defining a sustainable transition from fossil fuel-based economy to an economy based on renewables	A further increase in renewable energy investment ranging from 4 to 10 times higher than the current value is required to attain sustainable transitions under different sets of constraints.
(Qudrat-Ullah, 2013)	Analysis of the dynamics of electricity generation in Canada	More investments are required to close the demand supply gap in electricity generation and not only towards capital assets but towards Research and Development (R&D)
(Bassi, 2009)	Investigation on the relevance of contextualizing energy issues to provide support to energy policy formulation meant to find sustainable solutions to current energy and environmental issues.	The interrelations that exist between energy and society, economy and environment is likely to result in the emergence of various unexpected side effects and elements of policy resistance over the medium and longer term.

3 CASE STUDY: TANZANIA

This chapter gives a description of the energy system of the country chosen as the case study for this research. It discusses the energy resources, consumption, electricity generation, energy institutional framework, energy policies especially policies and other initiatives directed towards increasing the share of renewables in Tanzania. An insight on some of the challenges of the Tanzanian energy sector is also given.

3.1 Geography, Demographics and Economy

The United Republic of Tanzania is the largest country in East Africa with diverse ecosystems and climatic zones. It is endowed with abundant natural resources but is already showing vulnerabilities to climate change and extreme weather events, including droughts and floods. The mean temperature is projected to rise, and rainfall is expected to change its traditional patterns (African Development Bank Group, 2015)

Figure 3.1: Map of Tanzania

Source: www.mapsland.com

The current population is at 52,554,628 (Tanzania Statistics) and rising at 2.9% per year and it is forecasted to grow to 83,900,000 by 2040 (MEM, 2016). Urbanization is also increasing even though the majority of the population still lives in the rural areas. Tanzania has experienced sustained economic growth since 2000. The East African country has a GDP of 47.43 billion USD, an estimated GDP per capita of 879.19 USD per capita and growth rate of approximately 7.1 %. (Worldbank,2016). Its economy is largely service-oriented, with tourism accounting for half of GDP, while agriculture employs around two-thirds of the work force and generates around one-quarter of GDP. Tanzania's Vision 2025 estimates that the country's GDP per capita to increase to 3000 USD per capita with growth rate of 8% and envisages that Tanzania will be a middle-income country by 2025.

3.2 Energy Profile

Tanzania's energy potential resources include hydro, natural gas, coal, and other renewable energies (solar, wind, biomass, geothermal). Figure 3.2 shows the Total Primary Energy Supply of Tanzania in 2017.

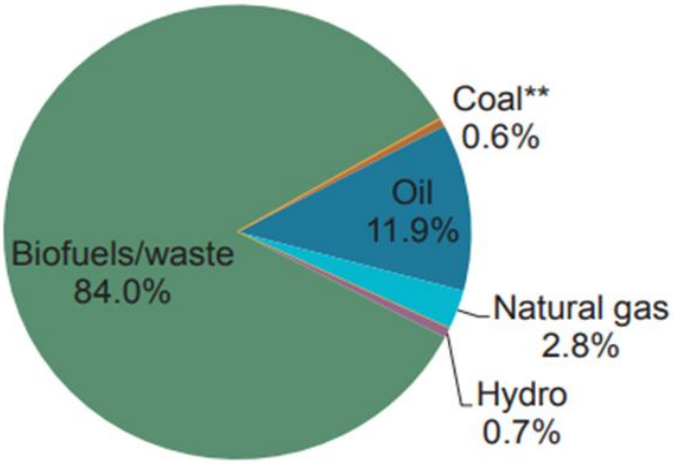


Figure 3.2:Tanzania: Share of Primary Energy Supply

Source: (International Energy Agency, 2017)

Despite the abundant resources for modern energy, 84% of a total 25.968 million tons of oil equivalent (MTOE) of the total primary energy supply in 2017 was from biomass (mainly firewood and charcoal), while other energy sources include petroleum (11%), natural gas (2.8%), hydro (0.7%) and coal (0.6%). (International Energy Agency, 2017). These proportions are a direct indicator of the country's level of development (African Development Bank Group, 2015).

The major change in Tanzania's energy sector has been the recent discovery off-shore of significant reserves of natural gas (57.25tn cubic feet) and this has put the country on the world energy map. The Government has been working hard to develop a Natural Gas Policy in response to gas sector developments. The policy deals with mid and downstream (how gas is used once it has been extracted) and will follow this up with a new policy document for upstream gas in due course.

Tanzania's hydropower potential is estimated at 4.7 GW, but so far only 12% of this potential has been utilized (Tanzania Energy, 2016). More so, due to extensive droughts in the country, the contribution by hydropower to the total supply has fallen dramatically. Tanzania has significant reserves of coal but has been used for industrial purposes, exploration for power is underway.

Table 3.1 shows the estimated energy resource potential in Tanzania (African Development Bank Group, 2015)

Table 3.1: Tanzania Energy Resource Potential

Source	**Resource Potential Estimated**
Hydro	4.7 GW
Small hydro Power	485 MW
Coal	1.9 Billion Tons, Songea Karoo belt in Southern Tanzania
Natural gas	57.25 tcf discovered
Biomass	More than 500MW
Solar	4.5kW/m2/day
Geothermal	650MW, East African Rift & Coastal areas 40°C< T < 130°C
Wind Power	Speed of more than 8 m/s (at heights of 30m)
Biofuels	Crops for ethanol and biodiesel (sugarcane, oil palm, jatropha)
Nuclear (Uranium), Tidal and Wave Power	Under Assessment

Tanzania is endowed with abundant, high-quality renewable resources. Despite this enormous renewable energy potential, development of RE resources is still gradual. The Indian Ocean coastline and areas in the Rift Valley shows promising wind speeds. The country is seeking to utilize its solar resources beyond the traditional lighting and phone charging functions, by investigating large PV projects (Tanzania Energy, 2016).

Tanzania’s location in the Rift Valley suggests a high potential for geothermal power generation; surveys indicate a potential of 600 MW. In 2006 and 2010, MEM, in collaboration with the Geological Survey of Tanzania, the German Federal Institute for Geosciences and Natural Resources and TANESCO, carried out surface exploration and conducted detailed studies in the Ngozi-Songwe prospect in the Mbeya region. Geo- thermometers showed that the reservoir temperature exceeds 200 °C (African Development Bank Group, 2015).

Tanzania imports all of its petroleum and petroleum products (including diesel and kerosene), for sale domestically by private businesses, or for use in electricity generation. At present, all petroleum products for general consumption are priced efficiently under a market-based approach and do not receive subsidies from the Government. The Government has also paid subsidies for the use of petroleum products as a fuel for the generation of electricity under the Emergency Power Programme (MEM, 2013).

3.3 Energy Consumption

Energy resources are consumed both directly (particularly wood fuel and charcoal for cooking and domestic heating) and used to generate electricity. For example, petroleum and natural gas are used in vehicles directly while much of the electricity provided to consumers, to businesses for production and to households for heat, light and cooking is generated using Tanzania’s own natural energy resources: natural gas, water, and increasingly other renewable sources such as solar power, biomass and wind. Figure 3.1 summarizes the sectoral energy use in Tanzania. The residential sector consumes the most energy, accounting for close to three quarters of the energy consumed in the country, the vast majority of which consists of biofuels and agricultural waste; 80% of biomass used in the residential sector is for household cooking, with about half of annual charcoal consumption occurring in Dar es Salaam (International Energy Agency, 2017)

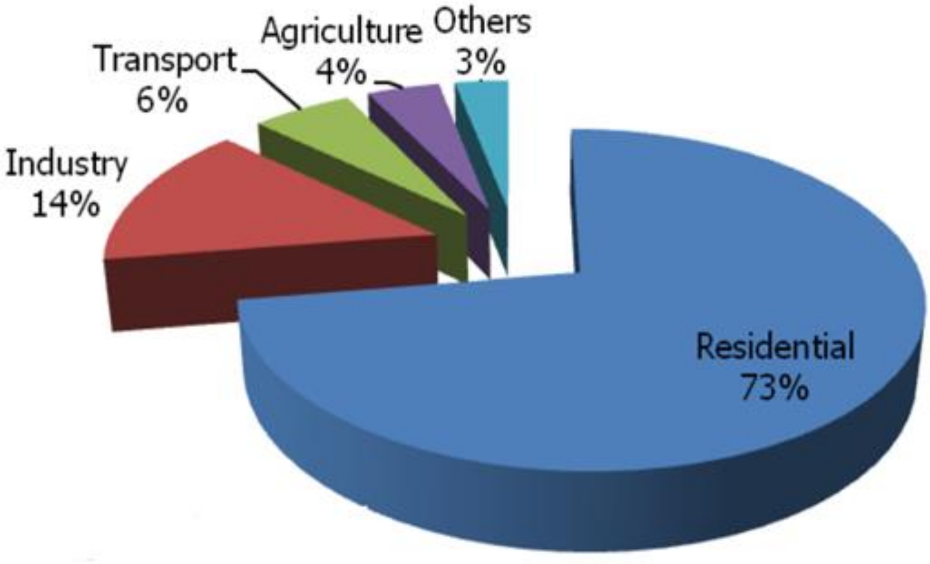


Figure 3.3: Tanzania Sectoral Energy Consumption

Source: (MEM, 2016)

In 2015, Tanzania’s energy consumption per capita was 0.49 tons of oil equivalent (TOE), one of the lowest rates in the world and only two-thirds of the average consumption in sub-Saharan African developing countries. However, energy use has been increasing rapidly owing mainly to accelerating productive investments and a growing population.

3.4 Electricity Generation

Electricity forms an important part of Tanzania’s energy sector as well as in the country’s economic, social and environmental sectors. The government of Tanzania has committed to developing electricity generation, transmission and distribution in-order to improve the country’s economy, increase access to the inhabitants of both urban and rural areas for improved wellbeing whilst at the same time being mindful of the environmental problems associated with the generation of energy. Tanzania has set out strategic plans to increase its economic growth, among them is Vision 2025 which will see Tanzania reach a middle-income country status with a target GDP growth rate of 8% per year and GDP per capita of $3000. The electricity sector is expected to play an important role in causing this turn around. Fig 3.4 shows Tanzania’s electricity sector road map to achieving Vision 2025.

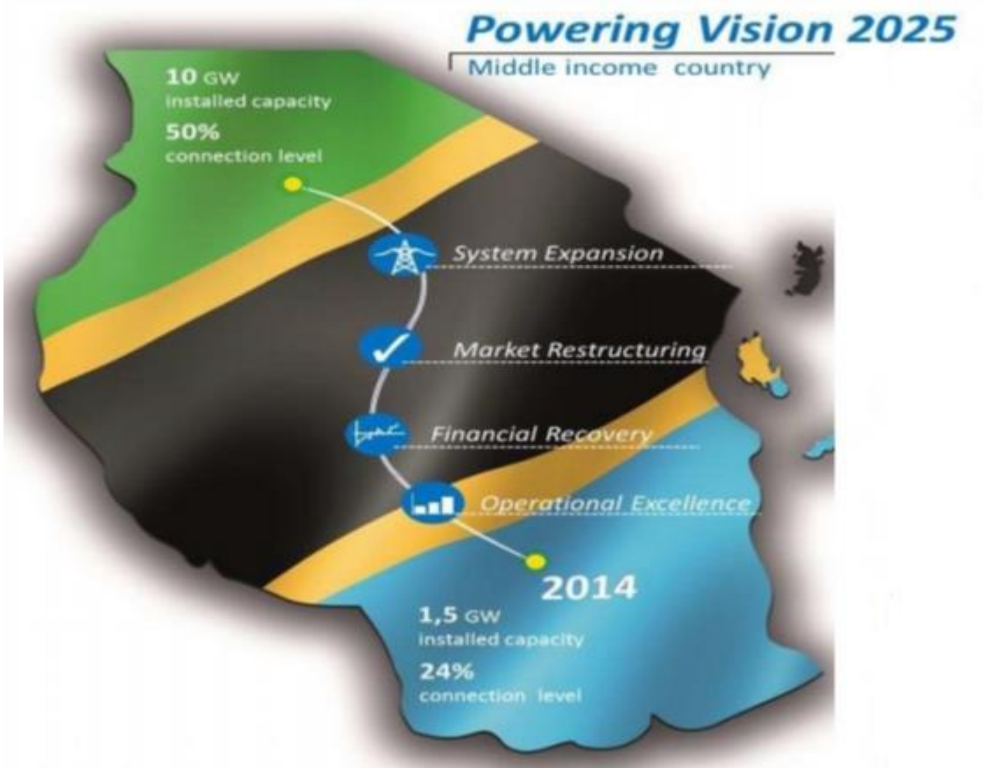


Figure 3.4: Tanzania Electricity Sector Roadmap to VISION 2025

Source: www.tanzaniainvest.com

Natural gas and hydro are to a great extent dominating the power generation portfolio of Tanzania. The installed power capacity is estimated at 1,583MW, of which 40% is hydropower, 45% natural gas, and 13% liquid fuel. (Tanzania Energy Statistics, 2015). A few plants are also based on biomass. Tanzania imports power from Uganda and Zambia and, in turn, exports power to Kenya.

Fig 3.5 shows the historical electricity generation by source. The dependence on hydro power has created supply security problems both historically and in recent years with frequent seasons of drought. Large hydropower as a share of total capacity declined by nearly two-thirds between 2002 and 2006 (from 98% to 45%), and now stands at just under 40% of available capacity (African Development Bank Group, 2015). This has caused load curtailment and power outages, as well as leading to high generation costs from oil-fired plants of Emergency Power Producers (EPP)s whose contracts have since been terminated.

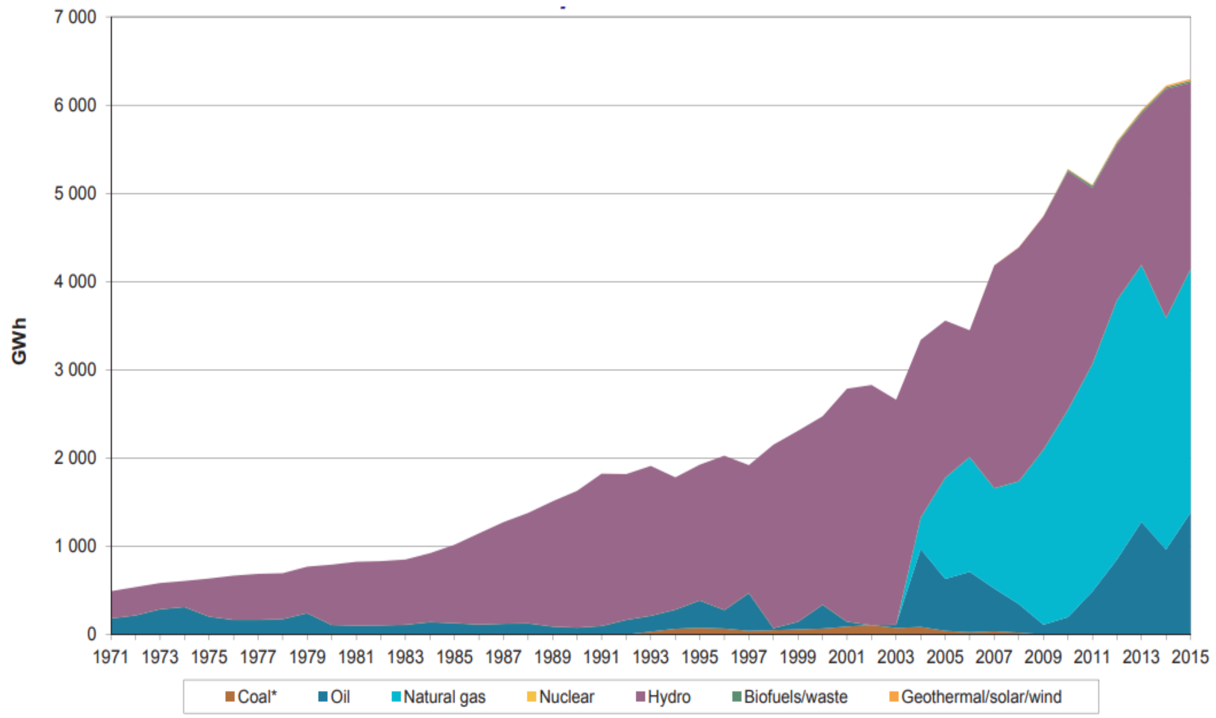


Figure 3.5:Historical Electricity Generation by source

Source**:** (International Energy Agency, 2017)

Table 3.2 summarizes the electricity generating capacity of Tanzania. (excludes smaller plants)

Table 3.2: Power Generating Capacity of Tanzania

Category	Fuel	Capacity (MW)
Independent Power Producers (1PP) s	Gas	202
	HFO	103
TANESCO	Gas	465
	IDO	7
	Hydro	566
Total Thermal Total Hydro		777 566
Total Generation		**1343**

The Government is planning to increase Tanzania's generation capacity by more than 500% in the next 10 years, from 1,583MW to 10,000MW in 2025 (MEM, 2016) and the production is expected to soar ten- fold from a current of 4,175 GWh in 2010 to 47,723 GWh in 2035. Table 3.3 gives a breakdown of the planned generation expansion projects by the Tanzanian government from its Power Master Plan of 2016.

Table 3.3: Planned Generation Expansion

Source	Capacity (MW)
Gas	2800
Coal	1200
Hydro	4700
Geothermal	300
Wind	650
Solar	200
Imports (Ethiopia)	400
Total	**10250**

However, to date most of these projects have not yet reached the construction stage despite the fact that the government has planned commencement of their operation in 2025 for most of them. The master plan cites that:

- Financing for coal fired power plant is challenging because of the international pressure against coal fired power due to greenhouse gas emission. In addition, disposal of bottom and fly ash and gypsum (by-product of Flue Gas Desulfurizer) is also a constraint in developing coal fired power plants.
- The availability of natural gas will be key in deciding its contribution to the generation mix
- In addition to vulnerability to climate change, environmental impact, resettlement of people, and huge initial investment cost are also negative aspects of hydro power development.
- The challenges in developing geothermal resource are high upfront investment costs; long lead time from conception to production of electricity; capital intensive and high

exploration cost and risk, inadequate capital resource to undertake necessary studies; remote location and limited infrastructures.

- Generation costs of solar and wind have dropped significantly but their intermittency still remain a challenge therefore it is important to mix their generation with conventional generation.

3.5 Electricity Consumption/ Demand

The average electricity consumption per capita in Tanzania is 108kWh per year, compared to Sub-Saharan Africa’s average consumption of 550kWh per year and less than half of the consumption of low-income countries (IRENA, 2014). However, the demand for electricity in Tanzania is estimated to be growing at 10–15% per year mainly to accelerating productive investments and a growing population. The 2016 Master Plan forecasts a demand of 87,880 GWh by 2040, up from a current estimated demand of 5,000 GWh. In a separate study however done by IRENA for the Southern African Power Pool, (IRENA, 2013) the forecasted electricity demand of Tanzania was set at 24,781 GWh. Figure 3. 6 shows the historical electricity consumption of Tanzania in billion kWh.

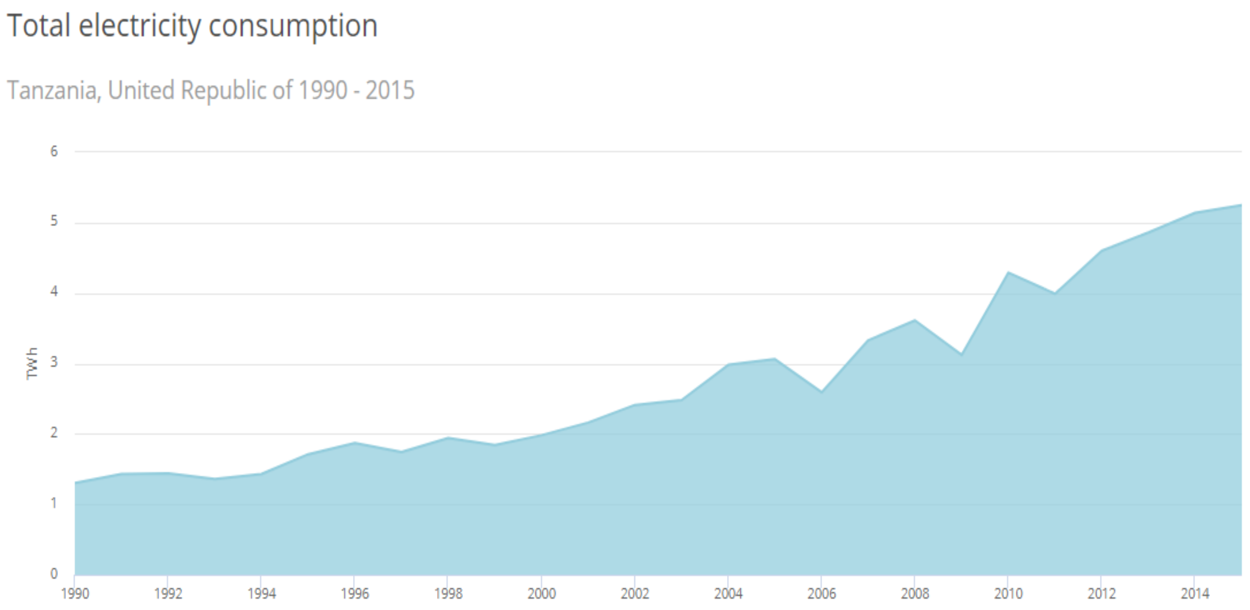


Figure 3.6: Historical Electricity Consumption, Tanzania

Source: IEA, 2017

Due to rural electrification programs which are ongoing, electrification rate reached an estimated 35% in 2015. Government has targeted to have the electrification rate of 50% by 2020. Under the conditions, the electrification rate is 64% in 2025, 76% in 2030, and 90% in 2035 (MEM, 2016)

3.6 Tanzania Energy Sector Challenges

Tanzania's energy sector faces a number of significant challenges. Amongst the most crucial as mentioned in a report by the African Development Bank, are:

- Increasing electricity demand as a result of increased productivity and population increase.
- Risk of disruption to generation and associated electricity price shocks due to the increasing unpredictability of hydropower which calls for diversification of the energy mix.
- Uncertain creditworthiness of the utility, TANESCO
- Low access to reliable electricity.
- The vastness of the country coupled with low population density makes grid extension too expensive for many difficult-to-reach areas this implies that mini-grid development through abundant renewable energy resources will be highly required.
- Health risks and environmental degradation from household reliance on biomass energy which raises the need to develop access to modern energy

3.7 Tanzania's Energy Institutions & RE status

To strengthen and modernize the energy sector, a series of policy reforms are transforming the way in which energy is produced, consumed and regulated in the country. Tanzania belongs to both the Southern African Power Pool (SAPP) and the East African Power Pool (EAPP). The country's energy sector is made up of various stakeholders, including national institutions, private-sector operators and NGOs. Figure 3.7 shows the structure of Tanzania's energy sector. As shown in the figure, the Ministry of Energy and Minerals' (MEM) responsibility is to develop energy and mineral resources and manage the sector. It is responsible for the formulation and articulation of policies to create an enabling environment for stakeholders. Promoting renewable energy is part of its mandate.

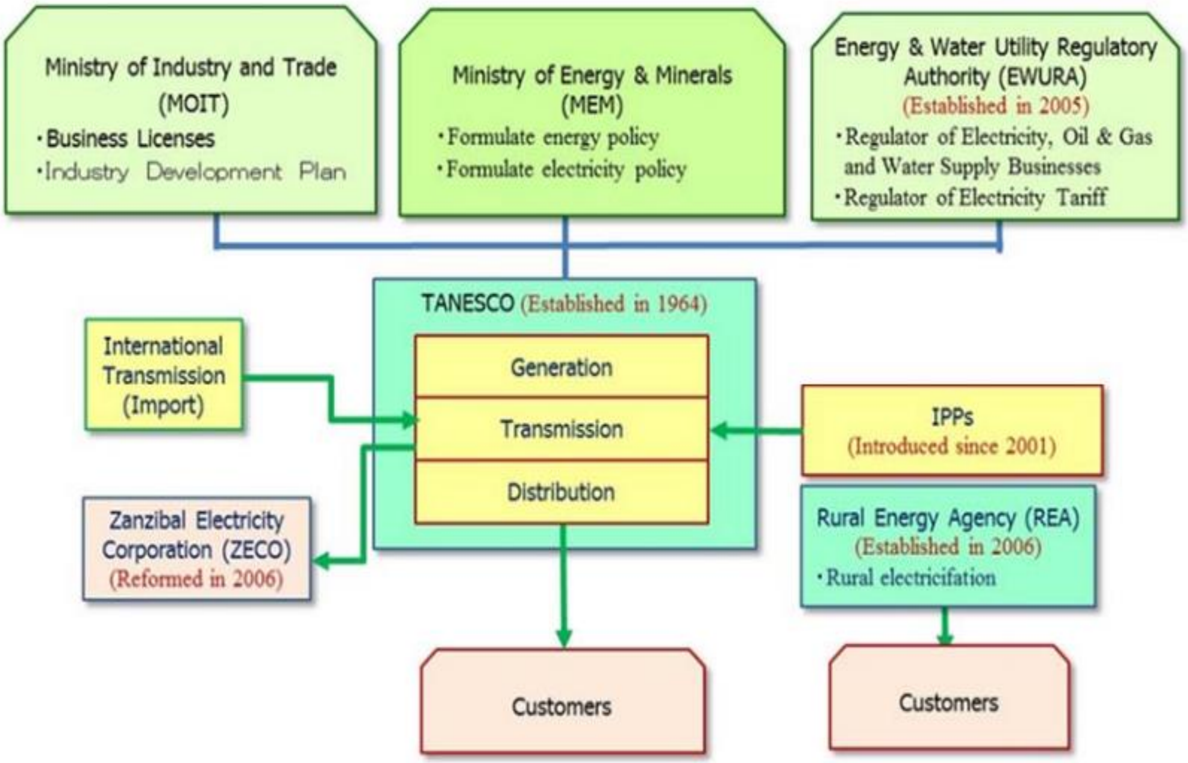


Figure 3.7: Institutional Framework and Market Structure of the Energy Sector

Source: (MEM, 2013)

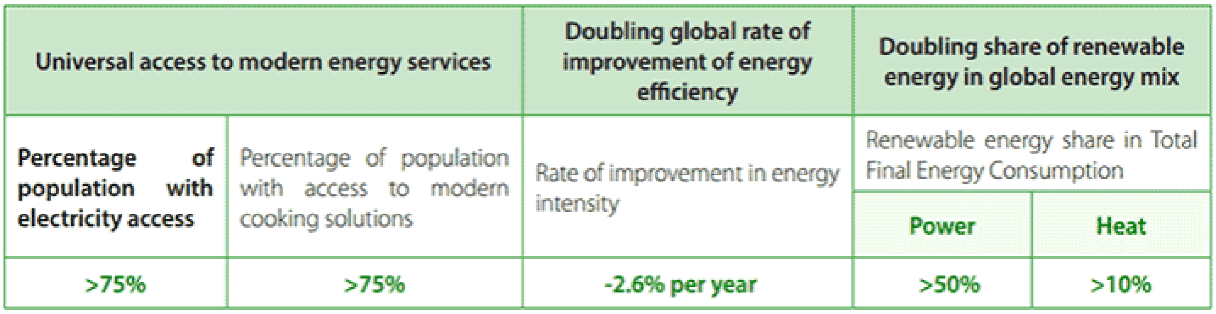
The energy utility, TANESCO operates in all segments of generation, transmission and distribution; operates its own power generation stations, purchases electricity from IPPs/EPPs, imports electricity from neighboring countries (Uganda, Kenya and Zambia), sells electricity to Zanzibar Electricity Corporation and distributes electricity to its customers.(African Development Bank Group, 2015). Small Power Producers (SPP)s are engaged in small renewable power development under the Small Power Purchase Agreements (SPPA)s to sell power to TANESCO or sell directly to retail customers. The Rural Energy Agency (REA) oversees developments in rural areas while an independent regulatory agency, Energy and Water Utilities Regulatory Authority (EWURA, is setting the rules for tariffs, licensing, monitoring and standards (MEM, 2013)

The government of Tanzania, has through its policies highlighted the objective of reducing dependence on fossil fuels for power supply, suggesting the development of renewable energy options. The threats of climate change have also prompted the government to diversify its energy mix and avoid the over reliance on hydro power. To create a legal and regulatory framework conducive to investment, it has instituted a range of energy-sector reforms, a major aim of which has been to attract private investment to boost electricity supply and thus meet demand. Some of the policies in place to enhance the development and utilization, of indigenous renewable energy sources and technologies include (Tanzania Energy, 2016):

- *National Energy Policy 2003*
- *Policies and legislation influencing biomass energy*
- *Environmental and land policy and legislation influencing renewable energy development*.
- *Renewable Energy Policy and Geothermal Energy Act*
- *Electricity act 2008:*
- *National Energy Policy 2015*

Table 3.4 summarizes Tanzania's targets for RE map 2030 with the aim of doubling the share of renewables by 2030 (IRENA, 2014)

Table 3.4: Targets for REmap 2013, Tanzania



Universal access to modern energy services		Doubling global rate of improvement of energy efficiency	Doubling share of renewable energy in global energy mix	
Percentage of population with electricity access	Percentage of population with access to modern cooking solutions	Rate of improvement in energy intensity	Renewable energy share in Total Final Energy Consumption	
			Power	**Heat**
>75%	**>75%**	**-2.6% per year**	**>50%**	**>10%**

4 METHODOLOGY “The System Dynamics Approach”

Herein presented is a system dynamics representation of the Tanzanian electricity sector with focus on electricity price and its subsequent effect on electricity demand. A system dynamics model with causal feedback loops is created using the Vensim Software PLE to carry out a countrywide analysis of the electricity sector of the Republic of Tanzania with the major objective of showing the dynamic behavior of the electricity system. The model focuses on long-term energy planning which provides an insight on radical changes to electricity generating technologies and the reflection of those changes on electricity price. Some of the radical changes considered for this study include:

- generating costs
- effects of technology maturity on profitability thus improving investment rates
- benefits of economics of scale
- carbon emissions
- institutional changes and interventions

The resultant dynamic behavior portrayed by the modelling exercise (for instance feedbacks and dynamic relationships between variables) is then used to provide useful decision support services for the planning of renewable energy integration in the country’s energy system. Figure 4.1 summarizes the procedure implemented in coming up with the System Dynamics Model.

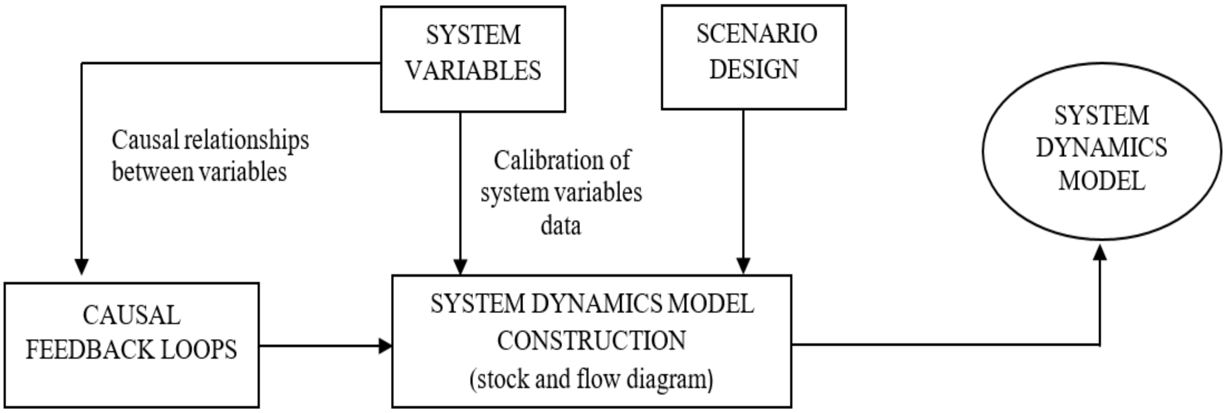


Figure 4.1:Procedure for System Dynamics Model Construction

As shown in Figure 4.1 the first step involves identification of key variables of the system. The causal relationships between the variables are identified and causal feedback loops are constructed. The causal feedback loops are combined with stocks and flows to construct the system dynamics model. The collected data on system variables is calibrated and used as input to the model. Scenario design creates the different scenarios that are used to adjust the input data to the model.

4.1 System Variables

The selected variables that make up the electricity system are identified with the focus being on electricity price ratio and energy demand (the major output variables). Table 4.1 classifies the system variables according to:

- whether they are exogenous (variable that is not affected by other variables in the system) or endogenous (variables whose values are determined by other variables in the system)
- type- this refers to how the values of the variables are used in the system dynamics model. The types include: auxiliary (used to estimate output variables), data (input variables to the model entered as a data series), level (variables that have accumulation within the system), flow (usually rate variables that affect level variables) and constant (unchanging system variables that are usually entered as a single figure)

Table 4.1: System Variables

Variable	**Unit**	**Endogenous/ Exogenous**	**Type**
Energy Demand	kWh	Endogenous	OUTPUT
Reference Energy Demand	kWh	Exogenous	Data
Price Elasticity of Demand	Dimensionless	Exogenous	Constant
Demand Supply Gap	kWh	Endogenous	Auxiliary
Demand Ratio	Dimensionless	Exogenous	Constant
Investment Rate	Dimensionless	Endogenous	Flow
Effect of Technology Maturity	Dimensionless	Exogenous	Data
Capacity under Construction	kW	Endogenous	Level
Rate of Completion	kW/year	Endogenous	Flow
Operational Capacity	kW	Endogenous	Level
Plant life time	years	Exogenous	Constant

Rate of Aging	kW/year	Endogenous	Flow
Capacity factor	Dimensionless	Exogenous	Constant
Load hours	hours	Exogenous	Constant
CO_2 emissions	Kg	Endogenous	Auxiliary
CO_2 emission factor	kg/kWh	Exogenous	Constant
Generation Cost	c/kWh	Endogenous	Auxiliary
Initial Generation	kWh	Exogenous	Constant
Reference Generation Cost	c/kWh	Exogenous	Data
Generation Subsidies	Dimensionless	Exogenous	Constant
Transmission Cost	c/kWh	Endogenous	Auxiliary
Transmission Subsidies	Dimensionless	Exogenous	Constant
Reference CO_2 emission price	c/kgCO_2	Exogenous	Data
CO_2 emission price	Exogenous	Endogenous	Auxiliary
Reference Electricity Price	c/kWh	Exogenous	Constant
Electricity Price Ratio	Dimensionless	Endogenous	OUTPUT

4.2 Causal Feedback Loops

Causal feedback loops have been extensively described in Chapter 2 under the review of System Dynamics Modeling (2.5.2). Feedback loops define the relationship between system variables and the direction of variable action. The most important feature is that the causal feedback loops can be used to estimate the causal relationships between related variables (Trappey et al., 2011). The identified system variables are used in the development of the causal feedback loops. The Causal Loop Diagram (CLD) of the electricity system as shown in Figure 4.2 shows 2 feedback loops, one balancing loop (negative feedback) and one reinforcement loop (positive feedback).

4.2.1 The Balancing Loop “Demand-Supply”

The dynamics of electricity supply to satisfy electricity demand is shown by the balancing loop, (B) in Figure 4.2. This loop is driven by the demand-supply gap. The demand supply gap arises from the difference created between the electrical energy demanded and electricity supplied. In this balancing loop/ self-correcting loop the response of the variables in the loop to a change in the demand supply gap is in such a way as to counter-act /oppose the change. An increase in demand widens the demand supply gap therefore investments are made to construct more generating capacity and increase supply thus reducing the demand supply gap.

The extent of investment in a particular generating technology either fossil or renewable to increase capacity is largely affected by whether or not the technology is profitable. A more profitable technology will have better investments. This research defines this profitability factor as the level of commitment by Tanzanian authorities to develop a particular technology from their power expansion plans.

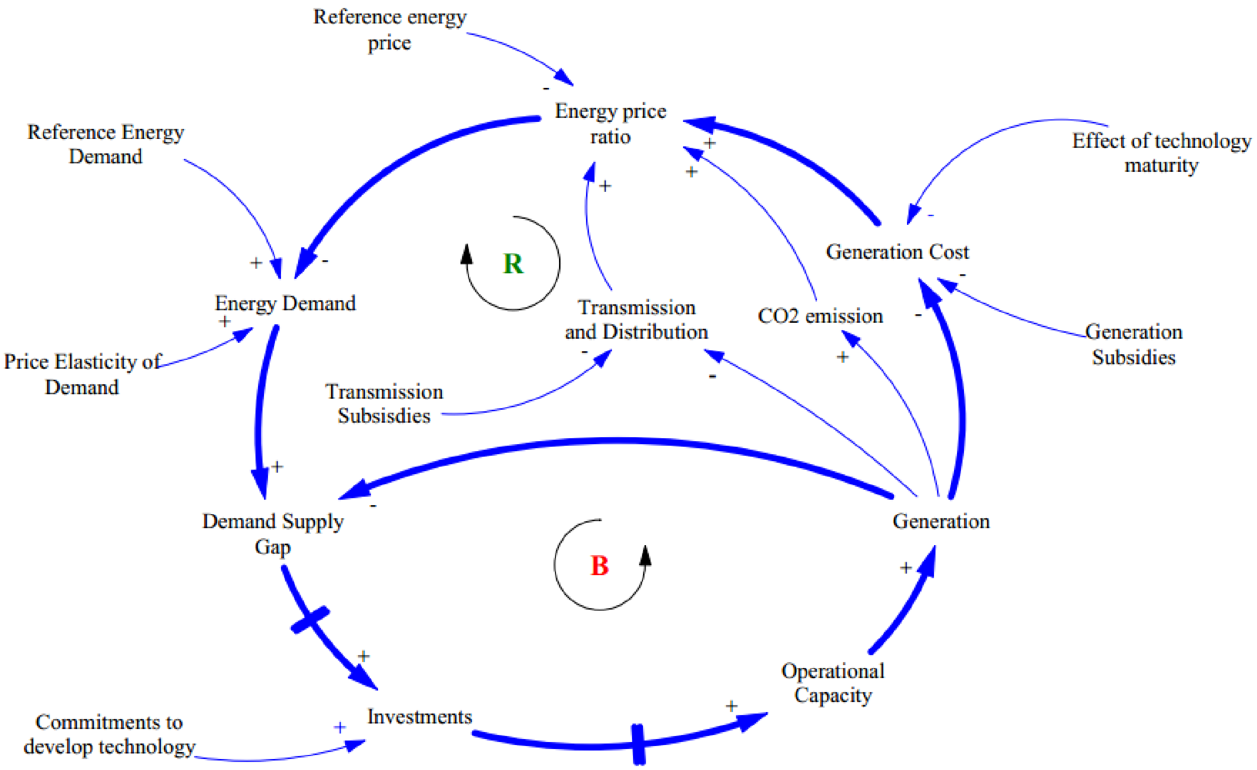


Figure 4.2: Causal Loop Diagram for the Electricity System-Emphasis on Balancing Loop B

Source: Own work (Vensim Software)

The increased capacity from investments made produces the electricity required to close or reduce the demand supply gap. It is also worth noting that the capacity factor and average load hours of each generating technology dictates the amount of electricity that is generated. Most fossil fuel technologies have high capacity factors and they can be utilized around the clock, however renewable generating technologies especially solar and wind have relatively low capacity factors and their intermittent nature also reduces their load hours.

The loop is also characterized by two (2) time delays:

- between demand supply gap and investments- there are several procedures that are followed in acquiring investments to increase generating capacity. There are applications and permits that need approval and these take time and causes a delayed response by the system to reduce the demand supply gap.
- between investments and operational capacity- time is also dedicated to the construction of the new additional capacity. In some instances, the construction time takes more time than anticipated thus causing further delays in the response of the system in counter-acting the change in the demand-supply gap.

In the event of reduction in the demand supply gap, the system also self corrects by reducing investments into construction capacity thus no more additions are made to operational capacity because the supplied electrical energy has managed to close the demand supply gap. And when supply exceeds demand, the operational capacity reduces further such that it generates only the electrical energy demanded. This can be detrimental to a system because after increasing the capacity by investing, only a fraction of the capacity will only be used and the rest not utilized despite its availability so the electricity provider will end up “stuck with assets” which he or she can no longer use to generate income. Therefore, an ideal situation would be one in which the system continues to create a demand that needs to be satisfied.

4.2.2 **The Reinforcement Loop “Demand -Price**

The dynamics of the effect of electricity price on electricity supply is shown by the reinforcing loop, (R) in Figure 4.3. This loop is driven by the electrical energy price ratio. If there is a change in the energy price ratio, the response of the variables in the loop is in such a way as to cause more of the change (amplify change). Say, the energy price ratio decreases, the system variables will respond in such a way as to cause further decrease and if the energy price ratio increases, the system responds by causing a further increase in the price ratio

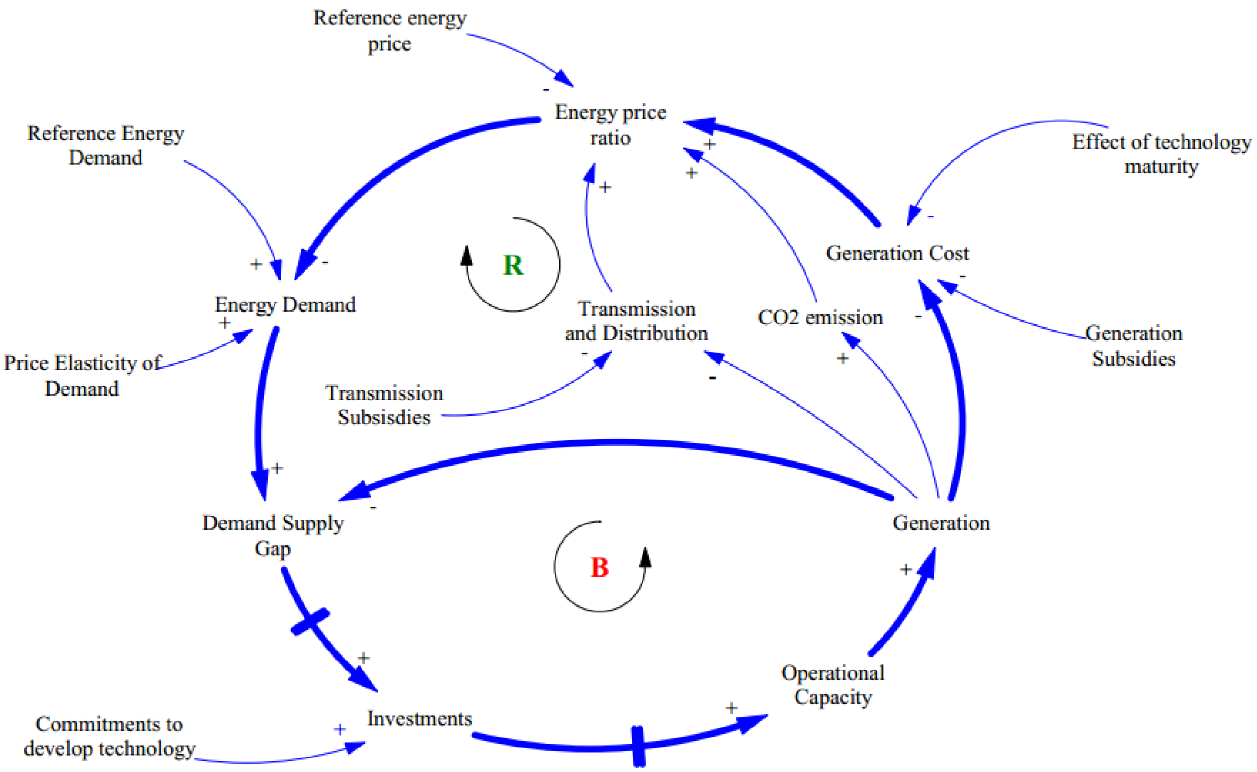


Figure 4.3: Causal Loop Diagram for the Electricity System-Emphasis on Reinforcing Loop R

Source: Own work (Vensim Software)

The energy price ratio compares the price of a generating technology to a reference price, which in this study is considered as an average electricity price in Tanzania. When the price of the generating technology becomes cheaper, it lowers the energy price ratio. A reduction in the energy price ratio, causes an increase in energy demand for that particular technology. Consumers respond to changes in price as illustrated by the concept of price elasticity of demand. This work focuses on the effect of price on energy demand, however there are other factors which influence growth in energy demand namely population growth and GDP increase. To account for the effects on energy demand by other parameters, the model defines a Reference energy demand which is determined exogenously and is calculated taking into consideration population growth and GDP increase throughout the modelling period.

An increase in energy demand due to the decrease in energy price ratio, increases the demand supply gap thus prompting investments to increase generating capacity in-order to meet demand. By increasing the generating capacity, the system benefits from “economies of scale” thereby making the generation cost cheaper. This research incorporates the effect of technology maturity on the generation cost. The cost of generating renewables is generally but with technological progression and increased efficiencies as well as increased scale of operation, the generating costs reduce. Cheaper generating costs, reduce the energy price of the generating technology and subsequently the energy price ratio. This further reduction in energy price ratio, increases the energy demand further and the variables in the loop continue to respond in such a way as to reduce the energy price ratio even further. Likewise, an increase in the price ratio, decreases demand and the system responds in such a way as to increase the price even further.

The model also considers 2 other factors that contribute to the pricing of a generating technology; transmission and CO_2 prices. Transmission costs are fixed but however, an increase in generation tends to reduce this cost per unit of electrical energy supplied. CO_2 prices on the other hand add on to the price of the generating technology, and the more energy generated, the more CO_2 emitted and the greater the CO_2 price. This phenomenon will result in higher prices for fossil fuel generating technologies and make renewable energy generating technologies more competitive especially now that the price per ton of CO_2 emitted continues to increase. An increased price ratio, decreases demand, therefore unclean technologies will be consumed less. A decrease in energy demand would be detrimental for the system as discussed in Section 4.2.1.

Introduction of subsidies for generating technologies and transmission are also considered in the preparation of this system dynamics model. Energy subsidies are any government action that concerns primarily the energy sector that lowers the cost of energy production, raises the price received by energy producers, or lowers the price paid by energy consumers (MEM, 2013). There are many different types of energy subsidies. Some have a direct effect on price, like grants and tax exemptions, while others act indirectly, such as regulations that skew the market in favor of a particular fuel or government-sponsored technology research and development as initiatives that policy makers can implement in-order to promote the generation of electricity from a particular fuel.

4.3 System Dynamics Model Construction

The causal feedback loops together with stocks and flows are combined in the construction of the system dynamic model shown Figure 4. 4. Equations for calculating the auxiliary system variables in the model are generated. In addition, the data used for the system variables in the model is also calibrated.

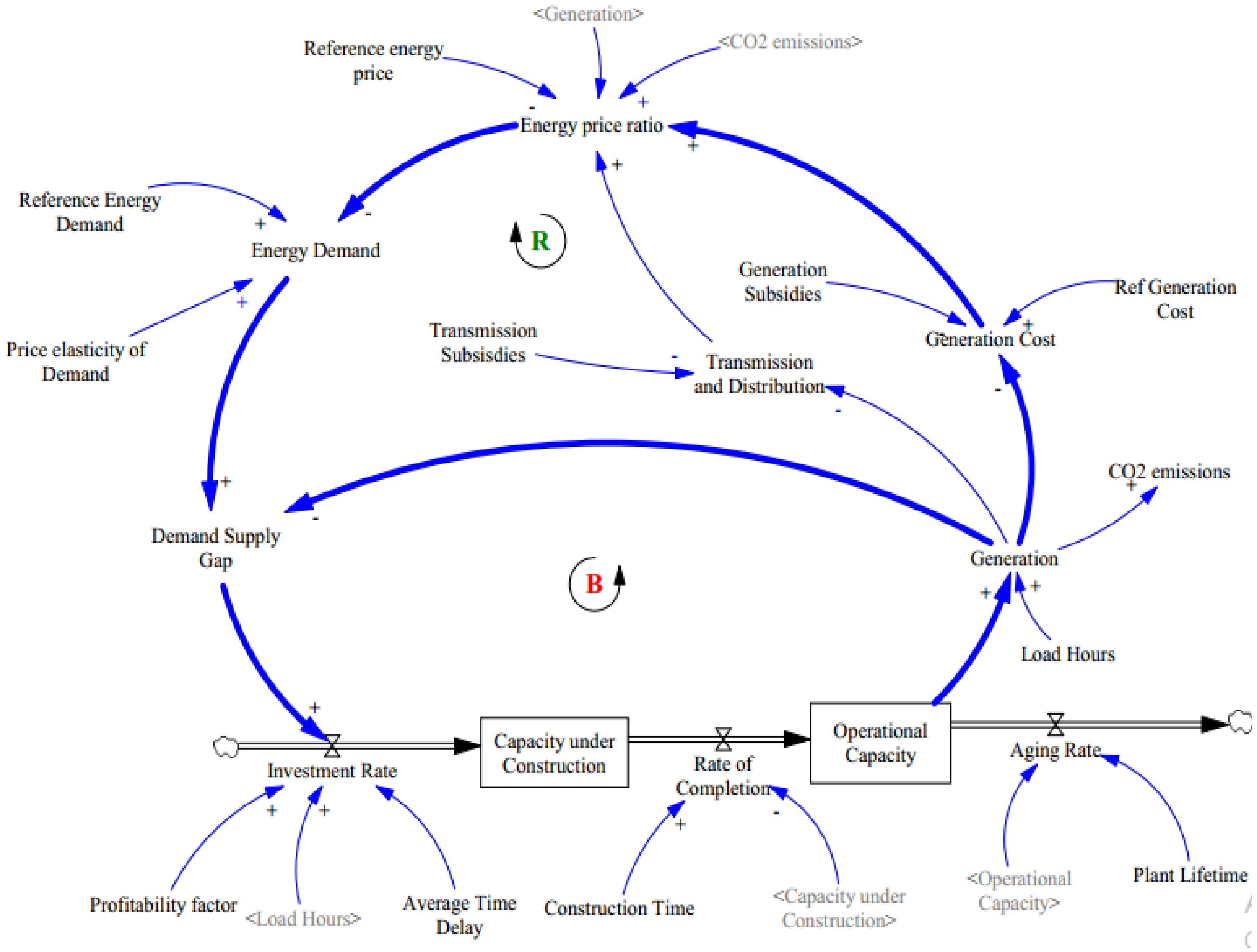


Figure 4.4:System Dynamics Model

Source: Own Work (Vensim Software)

The model makes use of a 2 vintages structure to represent the dynamics in the operational capacity (Qudrat-Ullah, 2016). The structure allows us to keep track of the actual capacity residing in the system. Operational capacity increases due to the additional capacity that is constructed after investments have been made while on the other hand decreases due to decommissioning of capacity that would have lived out its life time (captured by the aging rate flow variable). However, additional capacity can be considered operational after its completion, hence the flow variable, rate of completion is used to add the level in the operational capacity stock whilst at the same time used for reducing the level in the capacity under construction stock. The investment rate increases the level in the capacity under construction stock.

4.3.1 Modelling assumptions and boundaries

The modelling exercise uses Tanzania as the geographical location and data from the country is used for the variables in the system dynamics model. Assumptions made for particular system variables are explicitly explained in the section for calibration of data for system variables. The major data sources are:

- The Power System Master Plans for Tanzania (2012 &2016)
- The Eastern African Power Pool Master Plan (2011 &2014)
- Southern African Power Pool; Planning and Prospects for Renewable Energy, IRENA 2013
- IEA
- World Bank
- IRENA
- BP Statistics

The study considers only electrical energy and 3 energy generating technologies from available energy resources in Tanzania are used for the modelling exercise; Hydropower, Natural Gas Turbines and other renewables (combined as Solar PV and Wind). The other available resources; coal, geothermal and biomass are not considered in the modelling exercise considering the current status of planned projects from these resources in the power master plans. Hydropower is also renewable, but the operational characteristics of hydropower creates a distinction between hydropower generating technologies and other renewables. The supply of electricity is limited to electricity that is generated within the geographical boundaries of Tanzania, therefore electricity imports are not considered in the modelling exercise. A 5% ratio has been considered for all other sources of electricity that have not been considered in the model.

The study horizon spans the period 2010-2050. Forecasted values of variables that are not calculated in the model (exogeneous variables) are obtained from previous modelling exercises done in the data sources. The 40-year time horizon is sufficient enough for long-term impacts to take effect and especially allows technological progress of energy technologies to make an impact.

4.3.2 Calibration for system variables

4.3.2.1 Energy Demand

Energy Demand is modelled endogenously however with only the price feedback. When the price of electricity increases from a particular technology, the demand decreases. Conversely, when the price reduces, demand increases. Other drivers to energy demand like population and GDP are used to predict a Reference Energy Demand which is then entered exogenously to determine the effect of energy price on Energy Demand. Figure 4.5 shows the variables used in the determination of Energy Demand.

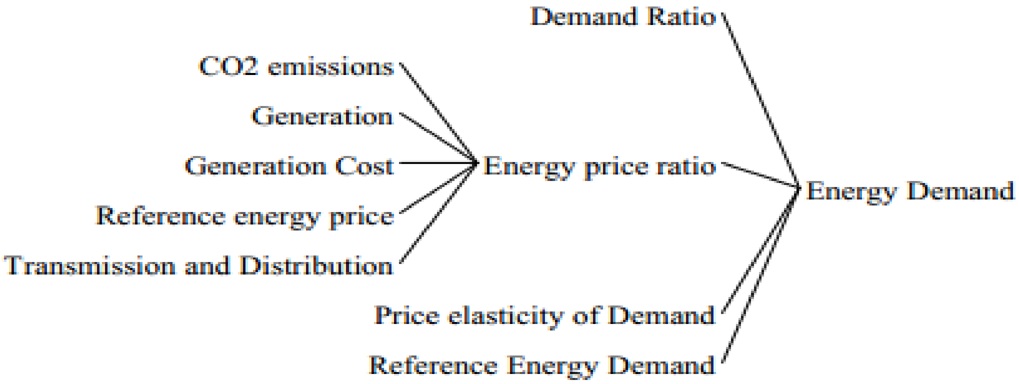


Figure 4.5: Energy Demand Causes Tree

Source: Own Work

Equation 4.1 is used for calculating Energy Demand:

$$Demand(kWh) = Reference\ Demand\ * Demand\ Ratio * Energy\ Price\ Ratio^{PED} \quad (4.1)$$

Where PED is the Price Elasticity of Demand

Reference Energy Demand

For the reference energy demand; the starting point was the consumption values of electrical energy from 2010 to 2015 provided by the IEA. The GDP and population data for Tanzania obtained from the world bank are used to project the reference energy demand. The projected figures of GDP growth rate population growth rate and energy demand in the master plans are also used, to determine an estimate of reference energy demand. The assumed values reflect an assumed decrease on demand growth, however the decrease is not so large as the economic and population growth for most developing countries, Tanzania included is expected to have a sustained growth within the period.

Fig 4.6 shows the projected reference energy demand values.

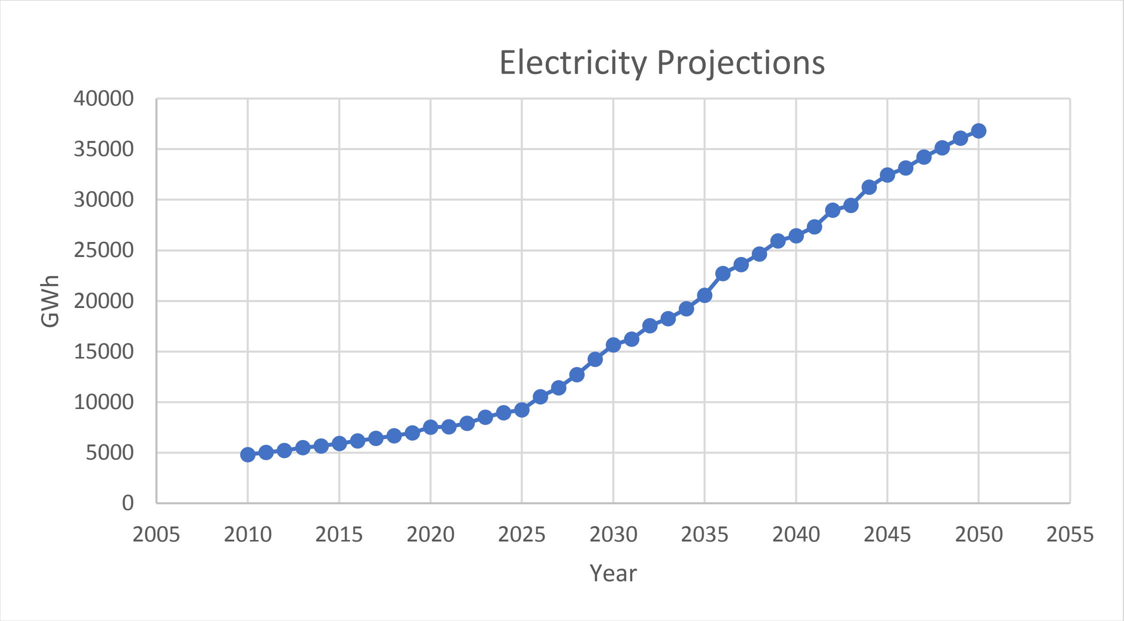


Figure 4.6: Projected Reference Electricity Demand for Tanzania

Source: Own Work

Demand Ratio

The demand ratio is used to split the demand for the various technologies considered. The figures used for the technologies correspond to the contributions made by the generating technologies to the overall electricity supply mix. The following figures were used

- Hydropower 40%
- Natural gas 50%
- Solar PV and Wind (Renewables) 5%

The other 5% was dedicated to other electricity supply sources which were not considered in the modelling process.

Energy Price Ratio

The energy price ratio is calculated endogenously as the ratio between the price of the energy generating technology and a reference price which in this study is considered as an average electricity price for Tanzania. The causes tree and calculation for Energy price ratio are presented in later sections.

Price elasticity of demand

The price elasticity of demand measures the responsiveness of consumers to changes in price. A high price elasticity signifies a consumer base that is very sensitive to price changes as is the case for the Tanzanian electricity market. Table 4.2 shows the average energy products elasticities from the work done by (Labandeira, Labeaga, & López-otero, 2017)

Table 4.2: Average energy products elasticities

	Short term	Long term
Electricity	-0.126	-0.365
Natural gas	-0.180	-0.684
Gasoline	-0.293	-0.773
Diesel	-0.153	-0.443
Heating oil	-0.017	-0.185

The effect of price on demand is a parameter whose value is based on long-term (Qudrat-Ullah, 2013). A price elasticity of -0.33 is used for this study.

4.3.2.2 Capacity Under Construction (CUC)

The capacity under construction is a system variable that refers to committed projects for energy generation infrastructure in response to the demand supply gap. Figure 4.7 shows the variables used in the determination of the capacity under construction.

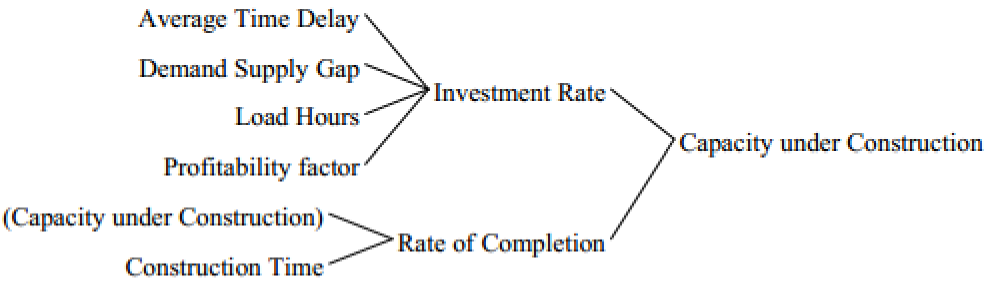


Figure 4.7:Capacity Under Construction Causes Diagram

Source: Own Work

The capacity under construction is a stock variable whose level at any point in time is given by the difference between the investment rate and the rate of completion. The equation for the capacity under construction is given as:

$$Initial\ CUC(kW) + \int_{t1}^{t2} Investment\ rate\left(\frac{kW}{year}\right) - Completion\ Rate(\frac{kW}{year})\ dt \qquad (4.2)$$

Investment Rate

The focus for investment assessment in this model is not to find an optimal or perfect investment cost (because each investment project differs from case to case and so do the costs), but rather to represent investment behavior for each generating technology. The investment rate is a nonlinear relationship of installed capacity and the profitability that capture constraints on investment rates. The investment rate is given by equation 4.3

$$Investment\ Rate(\frac{kW}{year}) = \frac{Demand\ Supply\ Gap(kWh)*Profitability\ factor}{Load\ hours(h)*Average\ delay\ time\ (year)} \qquad (4.3)$$

The demand supply gap given by equation 4.4, will result in commitment of investments to close the gap, however the profitability factor of a particular generating technology determines the fraction of the demand supply gap that will be closed by investments.

$$Demand\ Supply\ Gap\ (kWh) = Energy\ Demand(kWh) - Generation(kWh) \qquad (4.4)$$

This research defines this profitability factor as the level of commitment by Tanzanian authorities to develop a particular technology evident in the power expansion plans (MEM, 2016)

Rate of Completion

The rate of completion for additional generating capacity is given by 4.5

$$Rate\ of\ Completion\ \left(\frac{kW}{year}\right) = \frac{Capacity\ under\ Construction\ (kW)}{Completion\ Time\ (year)} \qquad (4.5)$$

4.3.2.3 Operational Capacity (OC)

A 2-vintage model (which incorporates delays in the commencement and completion of building additional energy infrastructure as well as losses in capacity due to aging) is used to track the operational capacity for this study. Figure 4.8 shows the variables used in determining operational capacity

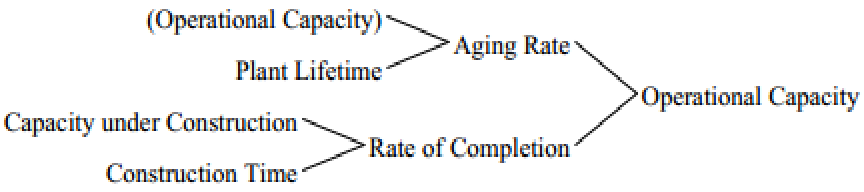


Figure 4.8: Operational Capacity Causes Tree

Source: Own Work

The operational capacity is calculated by equation 4.6

$$Initial\ OC(kW) + \int_{t1}^{t2} Rate\ of\ Competion(\frac{kW}{year}) - Aging\ Rate(\frac{kW}{year})\ dt \tag{4.6}$$

The loss in capacity due to plant decommissioning, is captured by the Aging Rate which is calculated from equation 4.7

$$Aging\ Rate\ kW/year = \frac{Operational\ Capacity}{Plant\ Lifetime} \tag{4.7}$$

4.3.2.4 Generation

The amount of electrical energy that is supplied to the system is accounted for by the Generation system variable. Figure 4.9 shows the variables used in calculating the Generation variable.

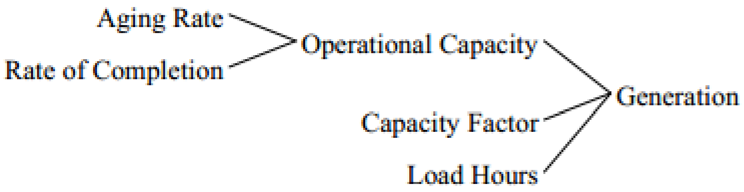


Figure 4.9: Generation Causes Tree

Source: Own Work

Equation 4.8 is used to calculate Generation:

$$Generation\ (kWh) = OC\ (kW) * Load\ Hours\ (h) * Capacity\ Factor \tag{4.8}$$

Plant parameters used in the model for the technologies considered during the modelling exercise are given in Table 4.3. The figures used were adopted from the Tanzanian master plan, SAPP plan for Renewables and IEA.

Table 4.3: Plant Parameters of Generating Technologies

	Natural gas	**Hydropower**	**Solar**	**Wind**
Service Years/ Plant Lifetime	25	50	20	20
Efficiency	0.6	0.85	0.201	0.174
Capacity Factor	0.80	Average:0. 4534 Dry Year: 0.3451	0.14	0.3
Load Hours (h)	8760	8760	2920	3500
Construction Time (years)	2	5	1	2
Initial CUC (2010) MW	180	250	30	30
Initial OC (2010) MW	450	540	40	40

4.3.2.5 Generation Cost (GC)

Figure 4.10 shows the variables used in determining the generation cost for each technology considered:

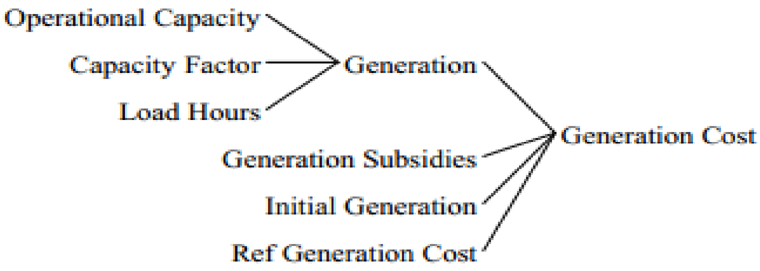


Figure 4.10: Generation Cost Causes Tree

Source: Own Work

The generation cost of each technology is calculated from Equation 4.9

$$GC\left(\frac{c}{kWh}\right) = Ref\ Gen\ Cost\left(\frac{c}{kWh}\right) * \left(\frac{Initial\ Generation}{Cumulative\ Generation}\right)^{li} * Generation\ Subsidies \qquad (4.9)$$

Where (li) is the learning index. The less mature technologies benefit from this phenomenon. Technology progression tends to reduce the generating costs of the less mature technologies. The technological progress for hydropower is assumed to be negligible being a mature technology with few remaining potential for development. The model estimates the following values of the learning index for the generating technologies adopted from (Vogstad, 2004)

Natural gas	0.05
Hydropower	0
Wind	0.2
Solar	0.2

Reference Energy Generation Cost (Ref Gen Cost) is determined exogenously. (Trancik, 2014) describes the behavioral change in the cost of electricity generating technologies and how renewable energy generating technologies are increasingly becoming cheaper as compared to fossil fuels. Figure 4.11 shows an extract from her study in which she shows that if costs keep falling at historic rates, then solar could be cheaper than coal after 2020.

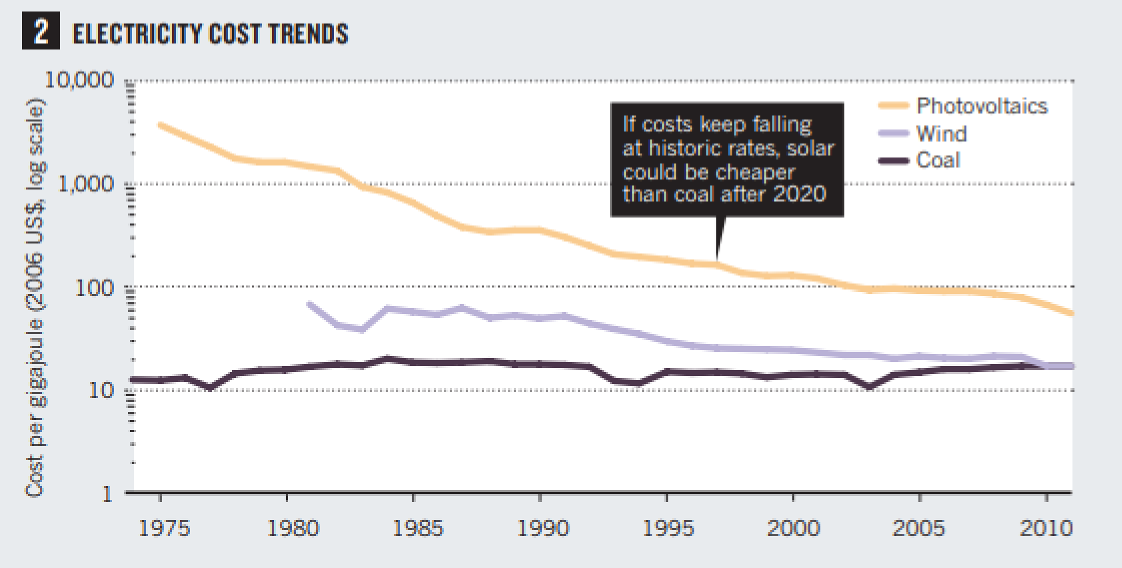


Figure 4.11: Electricity cost from Generating Technologies

Source: (Trancik, 2014)

Figure 4.12 also shows the trends of the levelized cost of electricity of solar

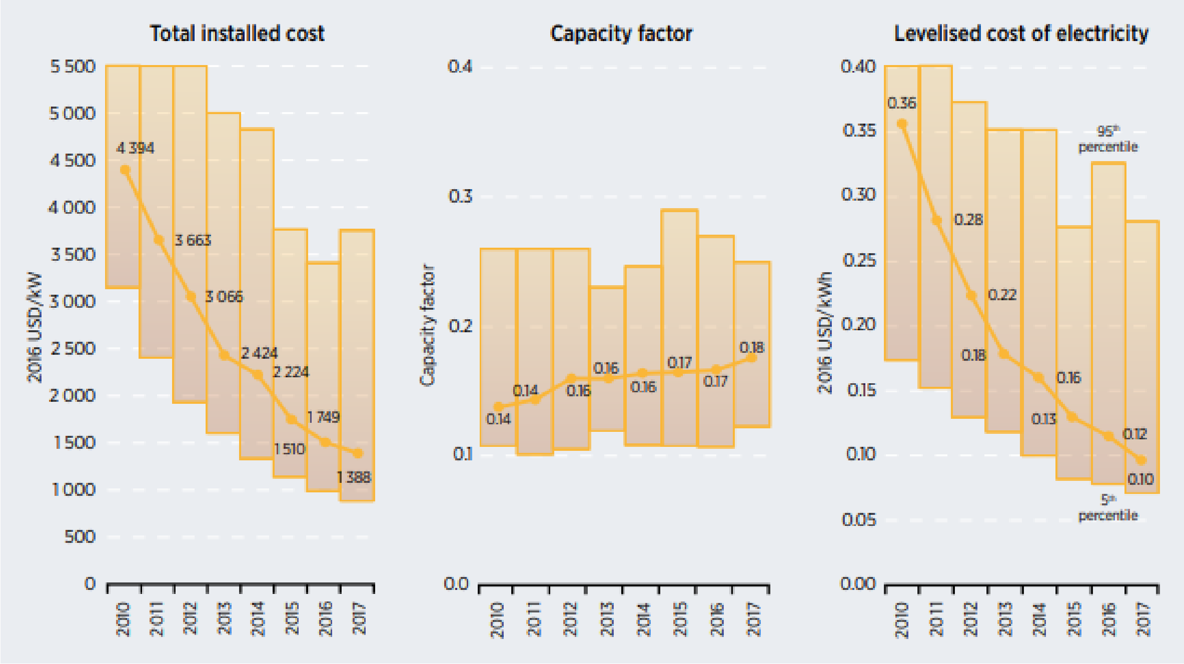


Figure 4.12:Trends of Solar Prices

Source: (IRENA, 2017)

Forecasted data on Levelized cost of Electricity of the generating technologies considered in this study is obtained from literature; (Varro, 2015), (IEA, 2018), (IRENA, 2013).

According to Tanzania’s energy policy on generation subsidies (MEM, 2013), no subsidies are being currently considered for generating technologies.

4.3.2.6 Energy Price Ratio

The Energy price ratio is the major output of in this modelling exercise. The response to energy price ratio of a particular technology is indicative of the sustainability of that technology. Figure 4.13 shows the variables used in determining the energy price ratio.

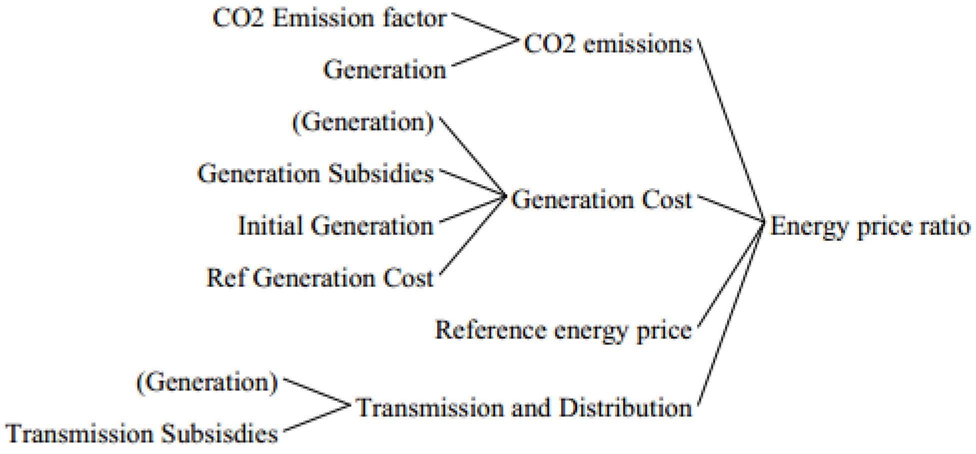


Figure 4.13: Energy Price Causes Tree

Source: Own Work

The Energy Price ratio (EPR) is calculated from Equation 4.10

$$EPR = \frac{(Transmission+Generation+CO2)costs}{Reference\ Energy\ Price} \qquad (4.10)$$

Where; $Transmission\ cost\left(\frac{c}{kWh}\right) = \frac{Total\ Transmission\ Cost\ (c)}{Generation\ (kWh)} * Transmission\ Subsidies$

The CO_2 price is given by Equation 4.11

$$CO_2price\ \left(\frac{c}{kWh}\right) = CO_2\ emission\ factor(\frac{kg}{kWh}) * price\ of\ CO_2\ per\ kg(\frac{c}{kg}) \qquad (4.11)$$

The reference energy price is an average electricity price for Tanzania for the entire modelling period; This model uses 12US cents/kWh as an estimate of an averagely affordable energy price in Tanzania.

4.3.3 **Scenario design**

Scenarios were designed using the level of commitment by Tanzanian authorities to develop particular technologies. For the reference or base case scenario, the level of commitment for each generating technology is calculated as the ratio of the planned generation expansion for that particular technology to the total planned generation. Table 4.4 summarizes the scenarios for the technologies used in the study.

Table 4.4: Scenarios

Technology	**Level of commitment**		
	Reference Scenario (Current Commitment)	Scenario_1 (Moderate)	Scenario_2 (High)
Natural Gas	0.28	0.35	0.5
Hydro Power	0.46	0.55	0.7
Renewables (Solar PV and Wind	0.08	0.15	0.3

5 RESULTS AND DISCUSSION

This chapter presents the simulation results of the modelling exercise. To begin with, strip graphs of the target output variables and major auxiliary variables for the Reference Scenarios of the generating technologies under consideration are presented. The strip graphs on Vensim Software use the same principle as the causes tree diagrams presented in the methodology chapter. They display small, simple graphs in a strip which makes it easy to trace the variables contributing to the results of the target variable. The strip graph plots a single variable on each graph of the strip and shows behavior for each loaded dataset. The output variables and major auxiliary variables whose results are presented are as follows:

- Output Variables:	Energy Demand, Energy Price Ratio
- Major Auxiliary Variables:	Demand Supply Gap Capacity Under Construction Operational Capacity

The second section of the chapter presents results for the output variables; energy price ratio and energy demand. The results include

- The energy price ratio curves for all the generating technologies using the Reference Scenarios.
- The energy demand curves in response to energy price ratio for all the generating technologies under their respective scenarios.

The final section of this chapter presents results for the major auxiliary variables under different scenarios for all 3 generating technologies. The scenarios presented as discussed in the methodology chapter are the different levels of commitment to promoting the 3 generating technologies by Tanzanian authorities as seen from their recent Power Master Plan (MEM, 2016)

5.1 Strip Graph Results

Herein presented are the strip graph results showing output and major auxiliary variables for all technologies considered under reference scenarios of the generating technologies

5.1.1 Energy demand

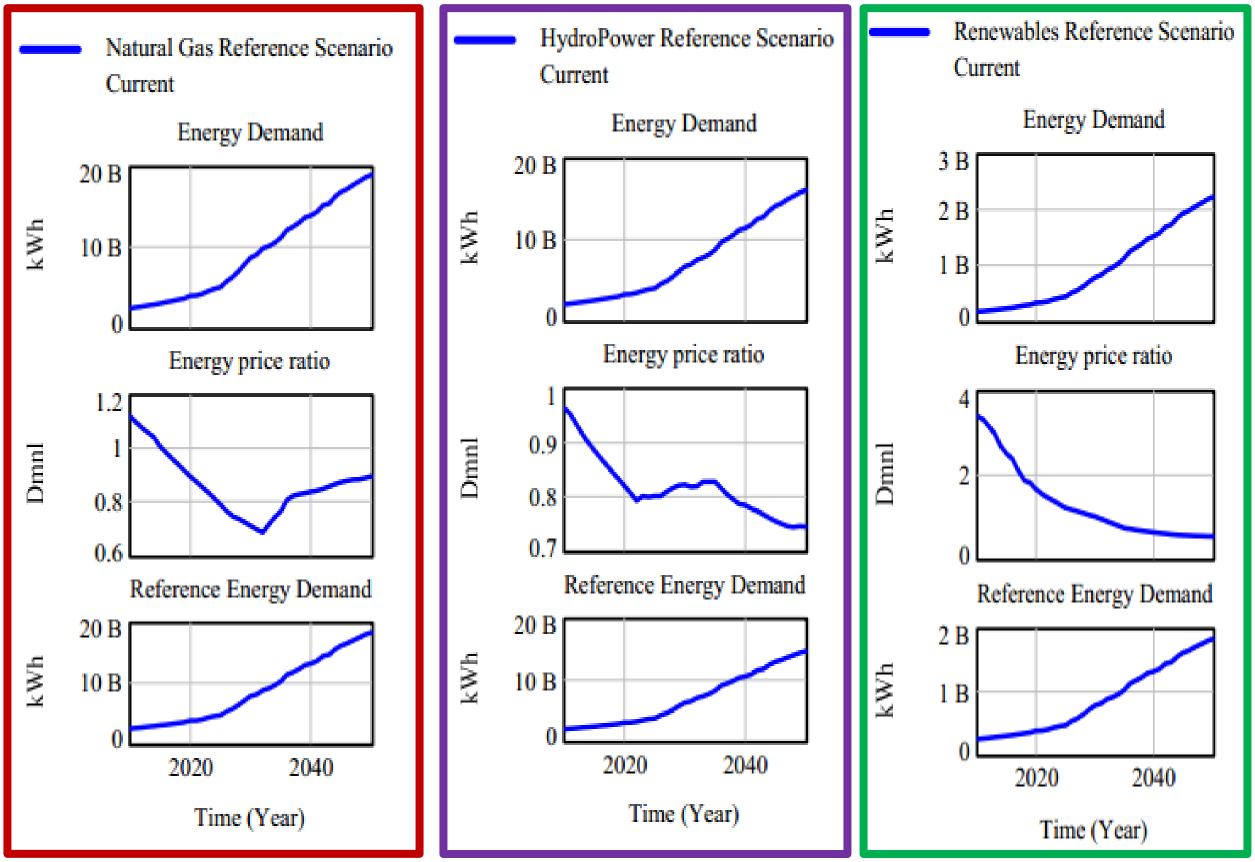


Figure 5.1: Energy Demand Strip Graph Results

The results show that energy price ratio is the major contributing factor in the outcome behavior of the energy demand curves for all 3 variables. Hydro Power starts off with the lowest energy price ratio between 2010 and 2020 and a corresponding positive response to the demand. Demand values for hydro power continue to increase with the decrease in its energy price ratio. Between 2020 and 2040 the energy price ratio of hydro power stabilizes but experience a slight increase towards 2040. After 2040, the energy price decreases slightly and stabilizes also causing positive response by the energy demand. It is worth noting however, that the energy price ratio of hydro power changes by slight values (from 0.96 in 2010 to 0.7745 in 2050) thus causing an estimated 10% positive change in the energy demand values of hydro power. The behavior of the energy price ratio is discussed fully in section 5.1.5.

Similarly, natural gas energy price ratios decrease from 2010 to 2030 and the energy demand between that period responds positively by over 15%. However, the energy price ratio increases slightly after 2030 from 0.7 to 0.9, subsequently slowing down the increase in energy demand. The energy price ratio results in an overall 4% positive change in the energy demand values of natural gas.

Renewables on the other hand, begin with an energy price ratio which is almost 4 times the energy price ratio of both hydro and natural gas and this is matched by a subsequent decrease in the energy demand at the beginning. The energy price ratio drops rapidly between 2010 and 2020 and continue to drop steadily and towards 2050, it becomes the lowest among the 3 technologies. Energy price ratio causes an overall estimated 30% change in the energy demand values of renewables.

5.1.2 **Demand Supply Gap**

The demand supply gap emanates from the difference created between energy supplied and energy demanded as discussed in the methodology chapter. Likewise, the strip graphs of the demand supply gap in Figure 5.2 show how generation and the demand contribute to the overall behavior of the demand supply gap.

Natural gas starts off in 2010 with a gap that is almost equal to zero because the initial generation slightly exceeds supply. The gap increases however to 2030 owing to the increasing values of demand responding to low energy prices. After 2030, the demand gap fluctuates and the generation responds by increasing to counter-act the increase. However, it responds with a delay. Between 2040 and 2050 the gap fluctuates till it finally starts dropping because of generation increase and at the same time a decrease in demand due to increasing price ratio ratios within the period.

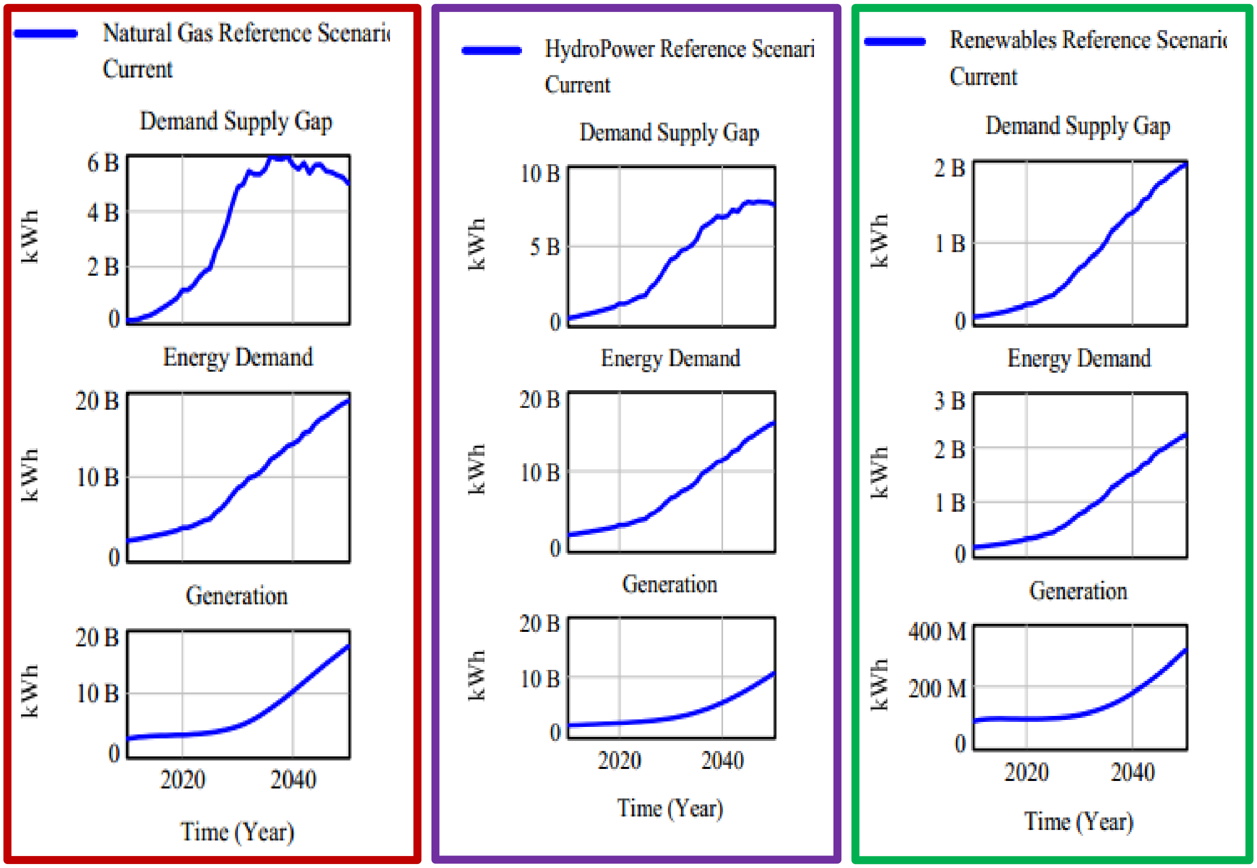


Figure 5.2: Demand Supply Gap Strip Graph Results

The demand supply gap of hydro power rises steadily within the period 2010 to 2050. This is as a result of the steady increase in demand owing to the energy price ratios. The generation responds with a delay which also keeps the gap growing. In addition, the capacity factor of hydro power in Tanzania has been greatly affected by long periods of drought and due to the rising impacts of climate change these droughts are expected to persist and further reduce the capacity factor.

Renewables also show a significant increase in the demand supply gap which is caused by the increasing energy demand. The generation also responds with a delay however not so large because of the relatively smaller time required to set up renewable energy infrastructure. The generation of renewables is also affected by the capacity factor which is still relatively small. However, with technological progression, capacity factors are expected to improve. This will help in maintaining the balance in the loop in such a way that the demand will not exceed way above what generation can supply.

5.1.3 Capacity under construction

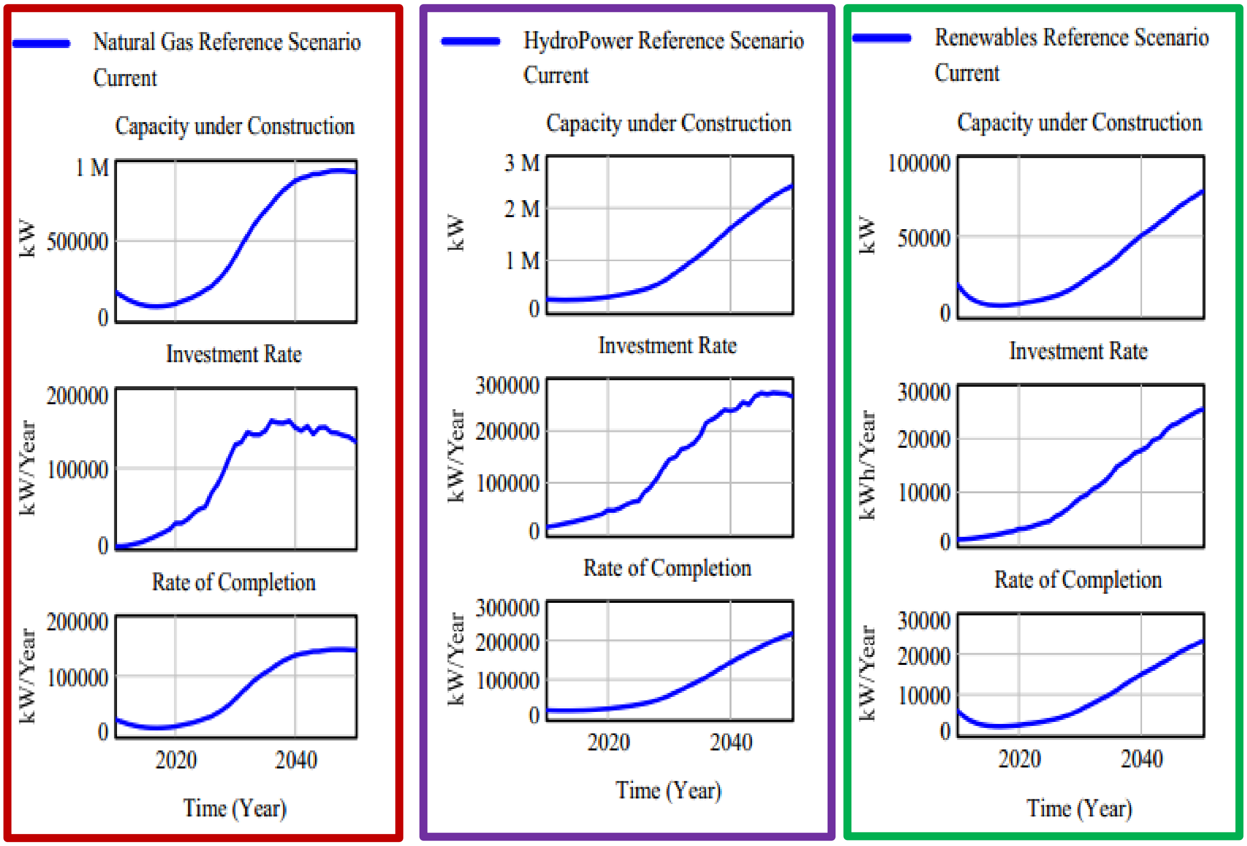


Figure 5.3: Capacity Under Construction Strip Graph Results

The capacity under construction is a stock variable whose level is maintained by inflows from investment rate and outflows measured as the rate of completion of the energy infrastructure under construction. The investment rate is driven by the demand supply gap and a profitability factor which in this research is used to define the measure of commitment by Tanzania's authorities to invest in a particular technology evident in their plans to build energy infrastructure from 2015 to 2040. In the reference scenario, hydro power has the highest commitment at 46% followed by natural gas at 28% while renewables have the least at 8%.

The capacity under construction for natural gas decreases because there is initially no addition through investments owing to the demand supply gap that starts almost at zero so the level in the capacity under construction stock reduces because there is only outflow of completed projects. The increased investments due to increased demand supply gap and a reasonably high commitment to build natural gas infrastructure by the Tanzanian authorities increases the capacity under construction. The capacity under construction however eventually stabilizes towards 2050 due to the reduced demand supply gap.

Renewables follow the same trend of a slight reduction in the capacity under construction due to low investment rate which are a combined effect of a small demand supply gap and very low commitment by the Tanzanian authorities to build renewable infrastructure. Relatively higher values of demand supply gap as years progress to 2050 increase the investment rate which in turn causes the increase in the operational capacity however with a delay due to the low commitment to build renewables infrastructure.

The operational capacity in the case of hydro power on the other hand, benefits from both demand supply gap and high commitment to build hydropower infrastructure by the Tanzanian authorities hence the increase in the capacity under construction.

5.1.4 Operational capacity

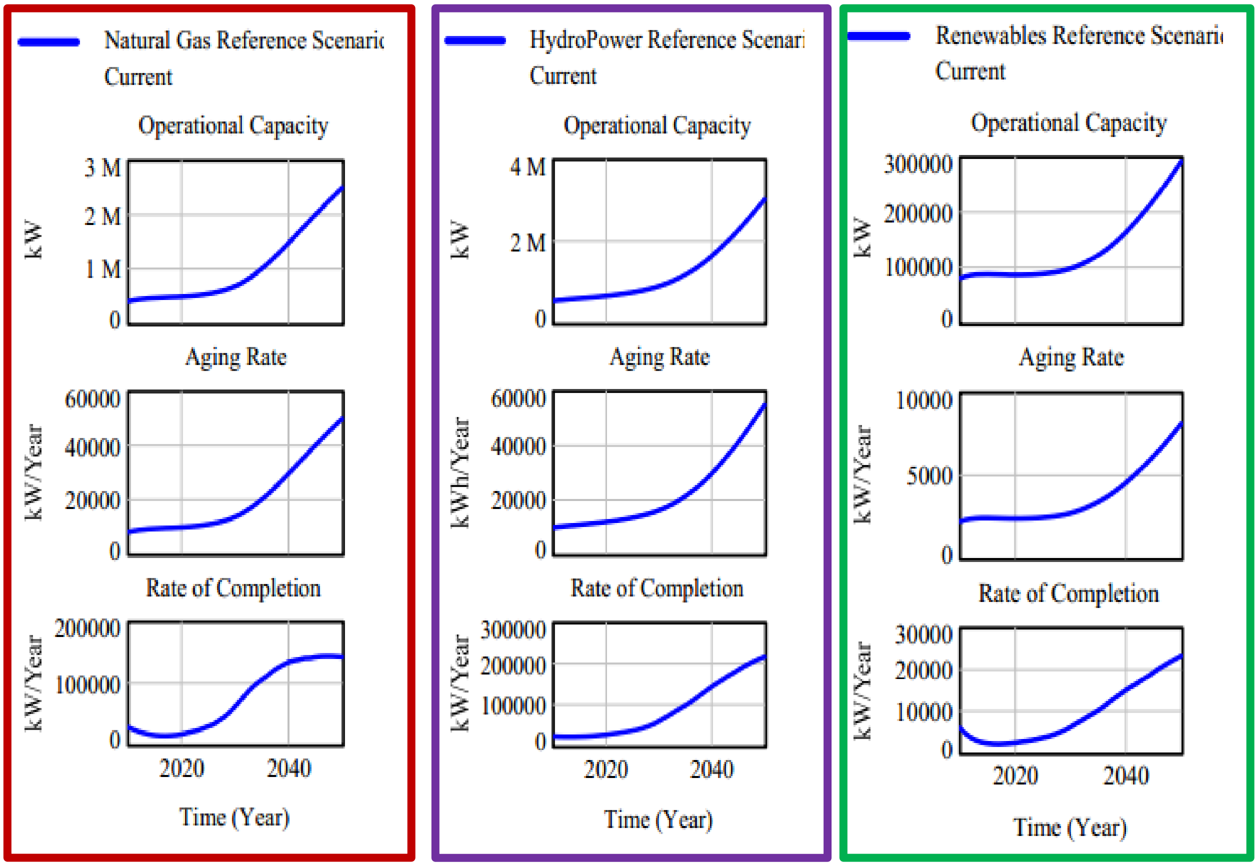


Figure 5.4: Operational Capacity Strip Graph Results

The operational capacity is the second stock in the 2- vintage structure of the model. The level in the operational capacity is maintained by incoming completed project measured by the rate of completion and decommissioned projects measured by the aging rate. From Fig 5.4, renewables and natural gas have a sluggish growth at the beginning of 2010 due to decreasing rate of completion which is affected by the behavior of capacity under construction. However, the growth of natural gas and renewables increases from around the year 2030 again owing to the behavior of the capacity under construction. Likewise, for the hydropower, the capacity under construction influences the rate of completion which in turn dictates the high growth that is witnessed in the operational capacity level of hydropower. The level in operational capacity is also decreased due to aging of the plants although this effect has slight delays because some plants continue running even after the lifetime has lapsed and equipment replacements and maintenance also prolong the plant life time.

5.1.5 Energy Price Ratio

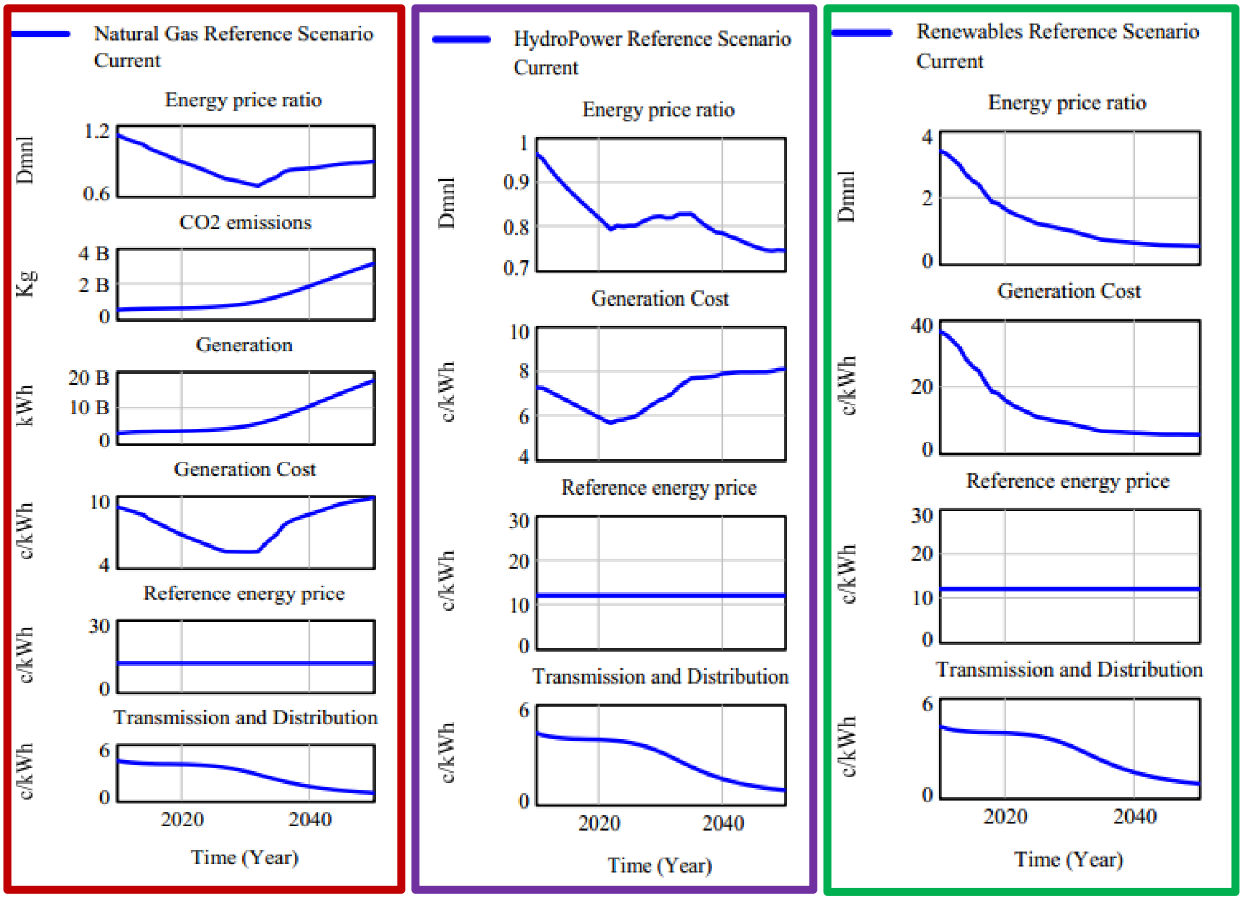


Figure 5.5: Energy Price Ratio Strip Graph Results

The behavior of the energy price is a combined effect of generation cost, transmission and distribution, CO_2 prices (for natural gas) and the reference energy price. An average electricity price of 12UScents/kWh in Tanzania was estimated as the reference energy price for all 3 technologies. The transmission costs also remain the same for all technologies as a fixed cost. An increased value of transmission is evident in the early years until 2030 this is because of the huge investments being made by the Tanzanian authorities in transmission and distribution infrastructure. The transmission costs eventually decrease due to the increase in generation which reduces the cost of transmission per unit of electricity transmitted.

The generation costs largely contribute to the behavior of the energy price ratio. Technology maturity, current global trends in technology prices as well as local considerations contribute to generation cost values. Hydro Power is a mature technology and therefore not strongly affected by technology maturity and does not rely on fuel whose prices are ever increasing, and this is depicted in the way its costs remain almost unchanged, fluctuating between 8cents and 6cents per kWh. The slight increase in generation costs between 2020 and 2030 is due to Tanzania's expansion plans which are aimed at increasing the capacity of small hydro power plants and small hydro power plants have slightly higher generating costs because of the scale of operation. For the last part of the modelling period, generating costs for hydro power remain almost unchanged and the slight decrease in the price ratio is due to the decrease in transmission costs.

Natural gas generation costs generally experience a downward trend up to 2030. In 2016, Tanzania discovered an estimated 2.17 trillion cubic feet (tcf) of natural gas in the coast region (Tanzania, 2016). The local availability of the fuel resource reduces the generating costs. However, not by a large margin as exploration costs to obtain the resource will be still contribute to the fuel price. In the later years of the modelling period, the effects of CO_2 are expected to negatively affect generation costs due to the increased generation which causes increased CO_2 emissions. The extensive use of natural gas to boost Tanzania's economy should also see an increase in fuel prices.

Renewables on the hand, benefit from the accelerating global decline of solar PV and wind prices which is driven by continuous technological improvements, including higher solar PV module efficiencies and larger wind turbines. (IRENA, 2017) reports a fall in cost of solar PV by almost three-quarters and those of wind by almost half in 2010 to 2017. The cost of renewables in Tanzania drastically reduce but however remain relatively higher than global prices till 2018 because of the current small-scale deployment of the technology. The costs only reduce to slightly match current global trends after 2025 due to deployment of the renewable technologies as noticed by the operational capacity values as from 2025. The decline in costs of renewables causes a subsequent decline in the renewable energy price ratio.

5.2 Output Variables Results

5.2.1 Energy price ratio for refence scenarios

Figure 5.1 shows the resultant energy price ratios of the 3 technologies under the reference scenario.

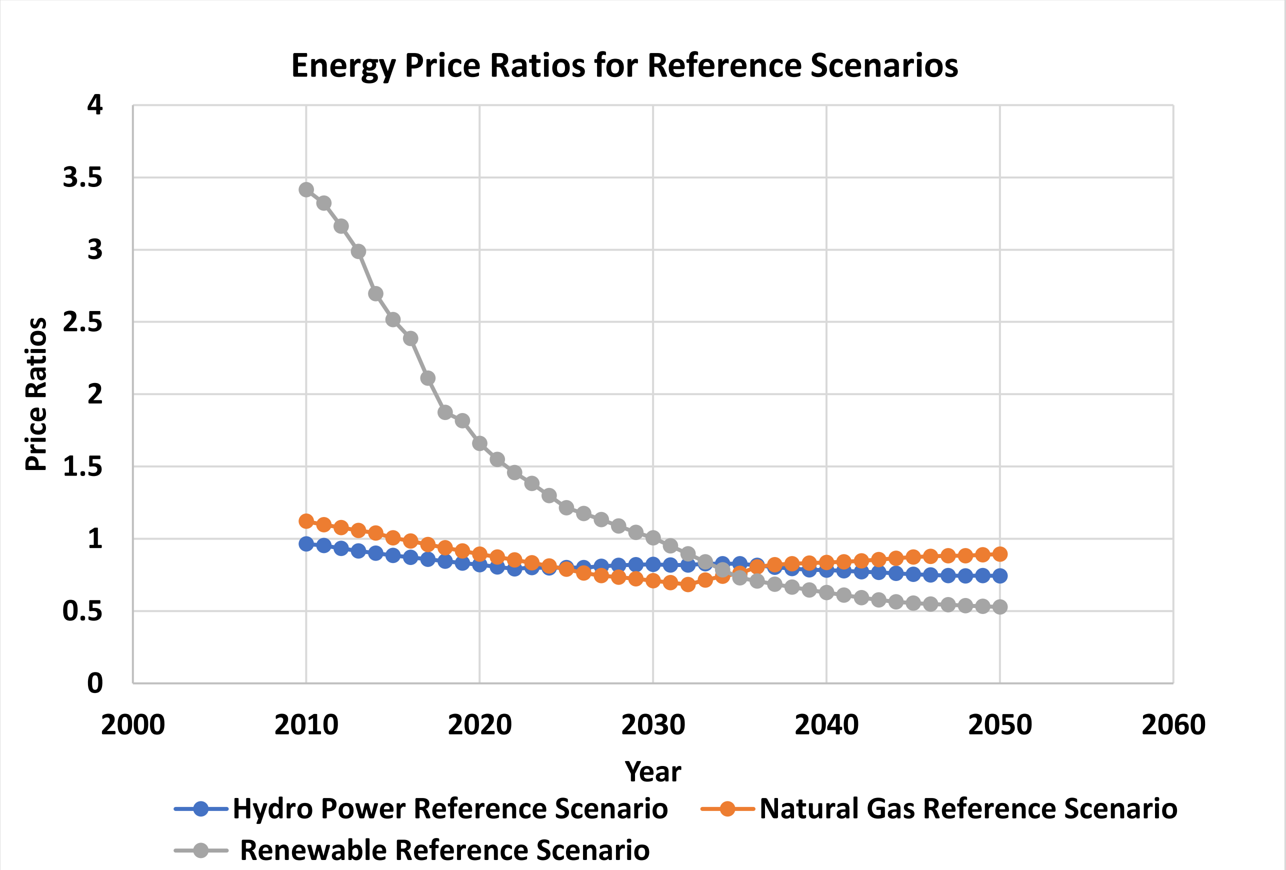


Figure 5.6: Energy Price Ratios for Reference Scenarios

This section compares the energy price ratios for the technologies considered. It is interesting to note that natural gas and hydro power technologies which are currently contributing the majority share in the electricity mix of Tanzania and thus driving the current electricity price in the country will experience a very small decrease in the energy price ratios during the modelling period. The price ratios of the 2 technologies will remain just below 1 which suggests that relying on these generating technologies will result in just a small decrease in the current electricity price. On the other hand, renewables experience a significant decrease in the energy price ratio. By 2035, the energy price ratio of renewables is expected to match that of hydropower and natural gas and towards the end of the modelling period, it reduces to 0.5 which suggests that deploying renewable electricity in Tanzania could result in the current electricity price of 12c/kWh cutting by half around the year 2050.

5.2.2 Energy demand response to energy price ratios

This section discusses the response of energy demand to the energy price ratios. Figure 5.2 to 5.4 illustrate the demand response to price ratios for all generating technologies under all scenarios.

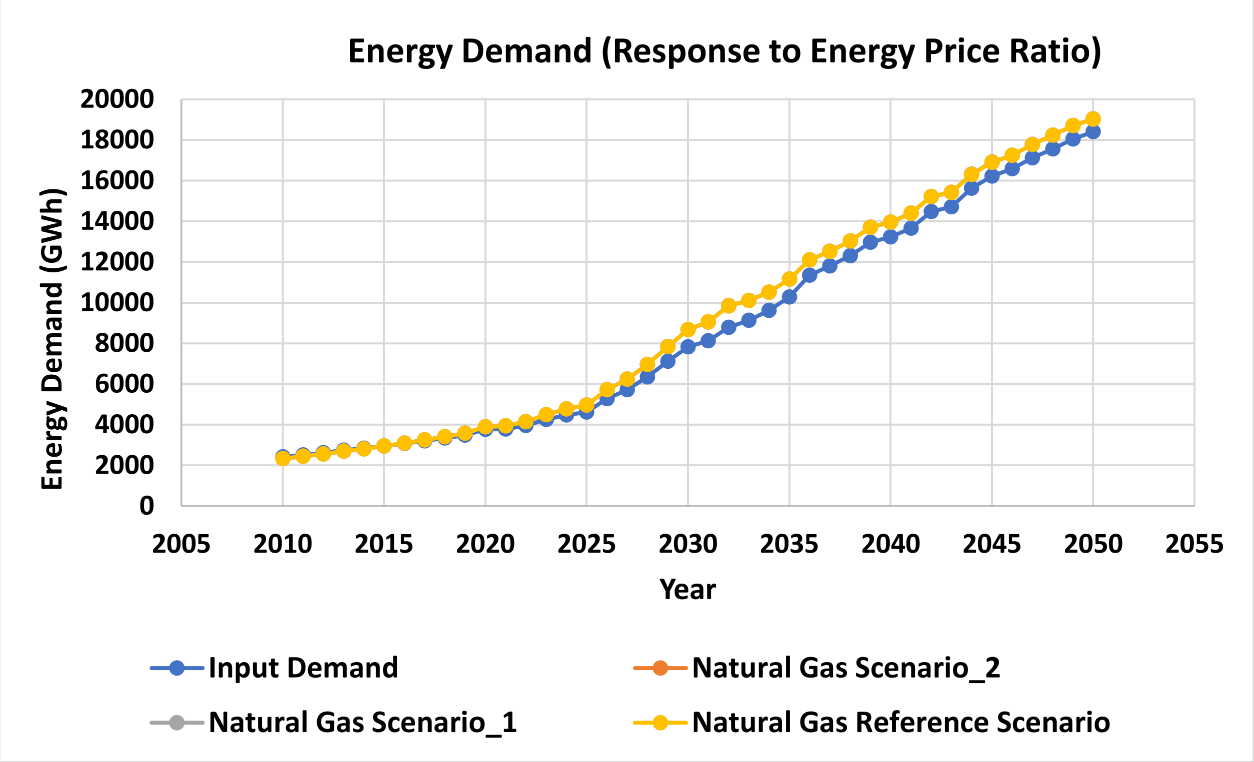


Figure 5.7: Natural Gas Demand Response Curves

The demand from natural gas generating technologies only increases slightly due to the slight decrease in the energy price ratio of natural gas during the modelling period. The energy price remains largely unchanged as seen in the previous section which suggests that very few consumers, especially those that cannot afford the current price are attracted by the reliance on natural gas as an energy generating technology. In addition, increasing the commitment to build natural gas infrastructure as seen in scenario 1 and scenario 2 does not help the situation either because as seen from Fig 5.2 the curves of the 2 scenarios are embeeded right under the curve of the reference scenario which means the demand response still remains the same.

Fig 5.3 shows the demand response curves of Hydro Power.

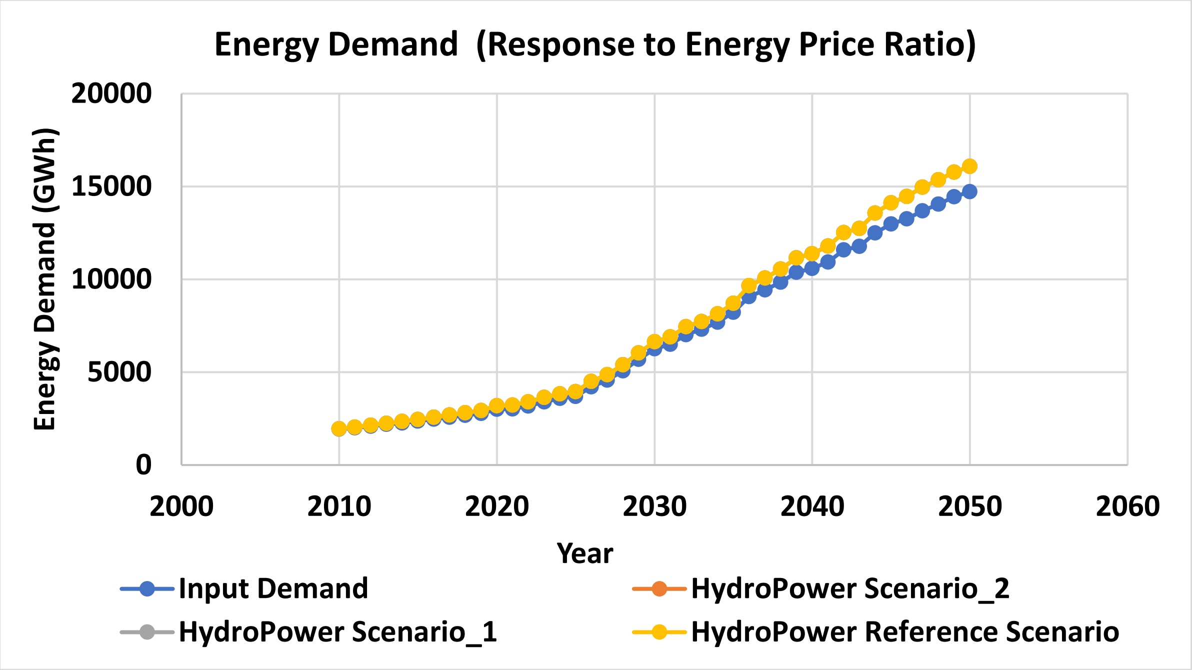


Figure 5.8: Hydro Power Demand Response Curves

Similarly, a small growth in demand is evident in the hydro power demand response curves due to the energy price ratio which changes by just a small fraction. An appreciable change however is noticed towards the end of the modelling period. Increasing the commitment for development of hydropower infrastructure also does not change the situation much as noticed from curves of scenario 1 and 2 that are embeeded just below the reference scenario.

Fig 5.4 shows the demand response curves of renewable energy. The decrease in energy price ratio of renewable energy results in an appreciable increase in the energy demand values. The resultant high energy demand values suggest that, more electricity consumers especially the low-income consumers (which make up the largest share of Tanzania’s population) are attracted by the deployment of renewable electricity. Increasing the commitment to deploy more renewables results in a further increase in energy demand as shown by the demand curves of scenario 1 and scenario 2. Thus, more efforts to deploy renewable electricity can actually increase the number of households with electricity access in Tanzania by over 30% as shown by the demand response curves in Figure 5.4.

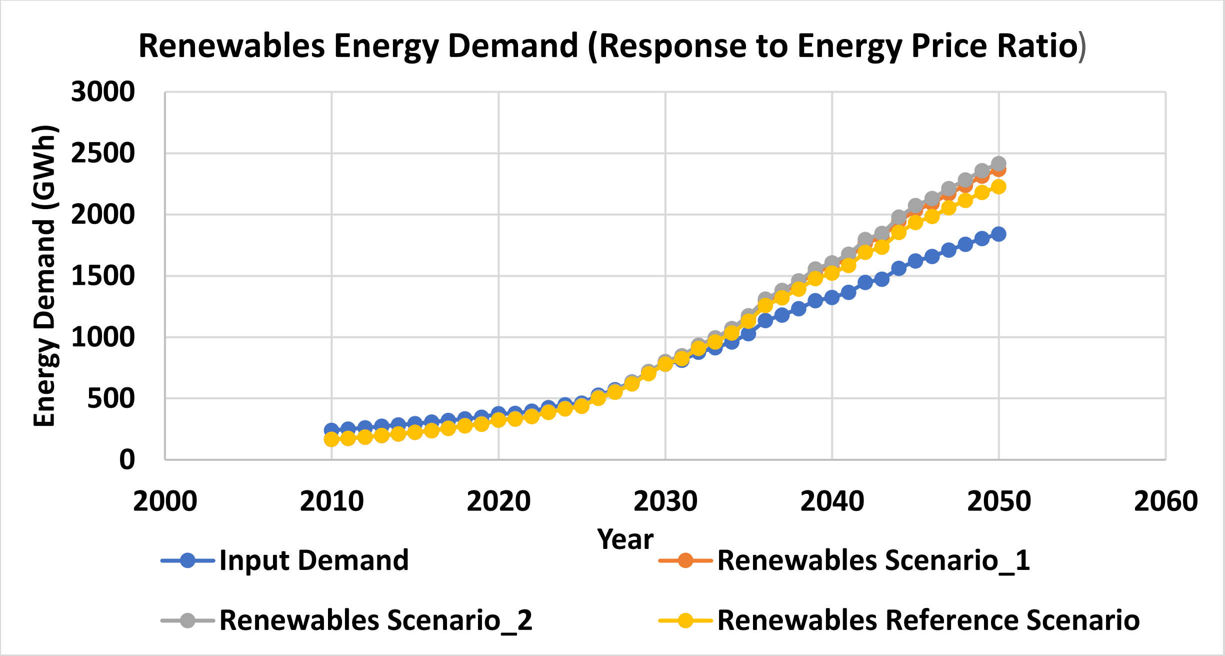


Figure 5.9: Renewables Energy Demand Response Curves

5.3 Scenario Results

This section presents results of major auxiliary variables considered for different scenarios. The behavior displayed by the curves is a direct effect of both the energy price ratio and the energy demand on the overall system for all the technologies. The curves are represented in Appendix 1.

The demand of natural gas remains largely unchanged to price ratios, therefore increasing commitment will increase capacity under construction, operational capacity and generation but eventually causes a big reduction in the demand supply gap. Ultimately, construction decreases and only a fraction of the built natural gas plants will be required to meet demand. A slightly better case is witnessed for Hydro Power. Energy price ratios maintain a small increase in the demand supply gap thus increasing capacity and generation throughout the modelling period in all the scenarios. However, eventually, construction slows down. For renewables, the price ratios and increased demand maintains a significant demand supply gap. More commitments increase capacity and generation which further reduces prices and increases demand for renewable electricity.

6 CONCLUSIONS AND RECOMMENDATIONS

The study successfully applied a system dynamics modelling approach to justify the need for increased commitment by the Tanzanian authorities in establishing renewable energy infrastructure. Energy systems do not exist in isolation, they are dynamic systems that change with time from influences of external parameters, therefore any solutions or initiatives for energy systems should be done after an understanding of the dynamic behavior of the energy system. For this reason, a model with feedback loops was prepared to analyze the dynamic variations in the social, economic, political, environmental, and technical aspects of Tanzania's energy system. Two major feedback loops were identified during the modelling process:

- a balancing loop which was counter-acting the changes in the demand. If at any time, there was demand increase, the variables in the loop would react in such a way as to increase capacity to close any gaps between the demand and the supply.
- a reinforcing loop which was reinforcing the changes in the energy price ratio. When there was a decrease in the energy price ratio, the demand responded by increasing which led to more generation and more generation reduced generation cost and further decreased the energy price ratio. Similarly, when the ratio increased, the variables in the loop would react to cause a further increase in the price.

This behavior of the model was used as a means to identify actions that policy makers could take to promote renewable energy and also justify that renewable energy among the 3 technologies considered in the study was the best candidate for increased commitment from Tanzanian authorities.

For the case of renewables, building more energy infrastructure for renewable energy increases renewable electricity generation. From the increased generation, the renewable system will thus benefit from economies of scale and technological progress while taking advantage of the fact that renewable generation does not emit CO_2. This will in turn reduce generation costs and also the energy price ratio. A reduced energy price increases demand which makes the system respond by increasing generation which further decreases the price ratio. Eventually the renewable energy system will be able to sustain itself without increased investments because its price will continue to decrease.

However, that is not the case with natural gas and hydropower because of the inherent limitations to increased generation that the two technologies possess.

For natural gas, increasing generation will help the system benefit slightly from technological progression. However, more generation from natural gas means more CO_2 and higher CO_2 prices which causes the energy price ratio to increase. So, the benefits of technology progression are cancelled out by increased CO_2 prices hence there is no noticeable change in the price ratio of natural gas, regardless of the level of commitment by Tanzanian authorities to build natural gas infrastructure. In a worst-case scenario, the CO_2 prices will outweigh the benefits of technological progress and the prices will continue to increase and thus reduce demand even further. Eventually, energy utilities will be “stuck” with energy assets that can no longer be put to use at full capacity until they age.

The same can be said about hydropower, the generating technology will not benefit from technological maturity because it is already a mature technology. Increased generation will benefit from economies of scale and thus reducing generation costs and the energy price ratio. However good hydro power sites where generation is economical eventually deplete so this becomes a limiting factor to the amount of generation that can be provided. In addition, Tanzania has suffered severe droughts and these droughts are anticipated to persist, therefore, the reduced capacity factor also negatively impacts the generation and generation cost. Eventually, the negatives cancel out the positive impacts on energy price ratio and therefore the energy price ratio remains unchanged regardless of the level of commitment by Tanzanian authorities to develop hydro power infrastructure.

A closer look at the capacity of both hydropower and natural gas that is to be constructed during the 30-year time horizon shows that huge capacities need to be constructed and be operational in a such a short space of time in order to meet demand. For hydropower, the capacity required doubles between 2030 and 2040 and doubles again between 2040 and 2050. Likewise, the capacity of natural gas is required to triple throughout the modelling period. Such large values are almost unachievable especially considering the pace at which Tanzania is building energy infrastructure for its committed projects. According to their latest Power Master Plan, (MEM, 2016) the government of Tanzania envisions an expansion of power generation capacity up to 4,915MW by year 2020 but only 2 years way from target, Tanzania has only managed under 1,600MW.

However, even if these huge capacities are achieved through large investments, the energy prices remain largely unchanged and at the worst are expected to increase beyond the 30-year time horizon which will put Tanzania at risk of remaining with “stranded assets” that cannot be put to full use because a small portion of the population will be able to afford energy from these technologies unless the government decides to subsidize the prices which will become hugely unsustainable as it will need to always apply the subsidies for the energy prices to be affordable for the larger proportion of the population.

Tanzania can therefore take advantage of the reinforcing loop (that continues to decrease prices and increase demand) by introducing renewable energy promotion policies, subsidies, carbon credits etc. at the present moment to force reduction in the renewable energy prices. The subsidies and other policies will only be meant to put the reinforcement loop in motion, “more like giving the process a head start”. Eventually, the renewable energy system will be able to sustain itself with the help of the reinforcement loop. Meanwhile, the reduced-price ratios of the renewable system will translate to more affordable energy and thus increases the proportion of people with access to electricity in Tanzania.

The reference energy price, which in this study was used as an average value that shows the electricity tariff in Tanzania also largely contributes to the energy price ratio. An ideal situation is when it remains stable and eventually drop. However, the value of the reference energy price is majorly influenced by technologies with the largest share in the generating mix and in the case of Tanzania the reference energy price is driven by hydropower and natural gas. The reference price in Tanzania is then subject to important external uncertainties like hydrology and fuel prices as it is driven hydropower and natural gas. Given TANESCO sells electricity at regulated tariff levels, which are not freely adjusted by the utility in the short term to reflect its sudden increase in costs, it has to carry such additional costs on its balance sheet unless it receives revenue grants from the government, passes them on to ratepayers through an increased tariff, or captures more profit from existing tariff levels by reducing its spending forward (Peng & Poudineh, 2016). This then diminishes the regulator’s ability to maintain tariff stability and this study shows that this increases the reference energy price and consequently the energy price ratios.

Tanzania needs therefore to introduce other generating technologies like Solar PV and Wind Energy to reduce its over reliance on hydropower and natural gas (whose prices are susceptible to negative externalities), in order to maintain tariff stability and in the best case a reduction in tariffs.

The major point that this study places emphasis on; is that a system dynamic approach to planning energy systems for any kind of intervention can never be over-emphasized. It is not only a matter of increasing energy capacity of the cheapest technology that is available at that present moment in order to close the huge energy deficit currently being experienced in Sub Saharan Africa because prices from that generating technology can remain largely unchanged, and the people in need of the energy most of which are from low income households will never be able to afford it. Therefore, it is important to analyze the dynamic behavior of energy systems in-order to implement sustainable energy solutions.

A recommendation for further study in this work, would be the incorporation of energy storage and flexible mechanisms that allow a higher share of variable renewable energy in Tanzania’ s energy system in order to investigate the dynamics of the system and identify opportunities for the sustainable introduction of energy storage which is currently a very expensive technology.

7 REFERENCES

African Development Bank Group. (2015). Renewable Energy in Africa - Tanzania Country Profile. *Renewable Energy in Africa*, 1–70.

Alsaif, A. K. (2017). Challenges and Benefits of Integrating the Renewable Energy Technologies into the AC Power System Grid. *Americal Journal of Engineering Research (AJER)*, (4), 95–100.

Andersen, J. (2015). Modelling and Optimisation of Renewable Energy Systems M ODELLING AND OPTIMISATION OF By, 130.

Aslani, A., Helo, P., & Naaranoja, M. (2014). Role of renewable energy policies in energy dependency in Finland: System dynamics approach. *Applied Energy*, *113*, 758–765. https://doi.org/10.1016/j.apenergy.2013.08.015

Bassi, A. M. (2009). An Integrated Approach to Support Energy Policy Formulation and Evaluation. *System*.

Bhattacharyya, S. C., & Timilsina, G. R. (2010). A review of energy system models. *International Journal of Energy Sector Management*, *4*(4), 494–518. https://doi.org/10.1108/17506221011092742

Bruckner, T. (1995). Modelling of Energy-Services Supply Systems. *Energy*, *20*, 941–958.

Cormio, C., Dicorato, M., Minoia, A., Trovato, M., Bari, P., & Orabona, V. E. (2003). A regional energy planning methodology including renewable energy sources and environmental constraints, *7*, 99–130. https://doi.org/10.1016/S1364-0321(03)00004-2

Domench, B., Ranboldo, M., Ferrer-Marti, L., Pastor, R., & Flynn, D. (2017). LOCAL AND REGIONAL MICROGRID MODELS TO OPTIMISE THE DESIGN. *Renewable Energy*. https://doi.org/10.1016/j.renene.2017.10.060

Frei, C. W. (2003). Dynamic formulation of a top-down and bottom-up merging energy policy model.

Grubler, A. (2013). Urban Energy Systems, 1307–1400. https://doi.org/10.4324/9780203066782

REFERENCES

Guanghong Zhou. (2015). *Low-Carbon City Initiatives in China : Planning Approaches , Dilemmas and Opportunities*.

Hake, J.-F. (2017). Energy Systems - Introduction International School on Energy Systems – ISES 2017, (July).

Hawkes, A. (2015). Energy Systems Modelling for 21st century energy challenges. In *Sustainable Gas Institute*. London.

Heilig, G. K. (2017). World Population Outlook.

Helgesen, I. (2013). *Top-down and Bottom-up : Combining energy system models and macroeconomic general equilibrium models*.

Herbst, A., Toro, F., Reitze, F., & Jochem, E. (2012). Introduction to Energy Systems Modelling, *148*(2), 111–135.

Hiremath, R. B., Shikha, S., & Ravindranath, N. H. (2007). Decentralized energy planning ; modeling and application — a review, *11*, 729–752. https://doi.org/10.1016/j.rser.2005.07.005

Hoffman, K. C., & Wood, D. O. (1999). Energy System Modelling and Forecastiong, (75).

Howells, M. (2013). Introduction to Energy Systems Analysis, (October).

IEA. (n.d.). International Energy Agency.

IEA. (2000). *Experience Curves for Energy Technology Policy Experience Curves for Energy Technology Policy*.

International Energy Agency. (2017). WEO 2017 Chapter 1: Introduction and scope. *IEA: World Energy Outlook*, 33–61. https://doi.org/10.1787/weo-2017-en

IRENA. (2013). SOUTHERN AFRICAN POWER POOL : Planning and Prospects Energy.

IRENA. (2014). A Renewable Energy Roadmap, (June), 56–65.

IRENA. (2017). *Renewable Power Generation Costs in 2017*.

Karas, T. H. (2004). SANDIA REPORT Modelers and Policymakers : Improving the

Relationships, (June).

Labandeira, X., Labeaga, J. M., & López-otero, X. (2017). A meta-analysis on the price elasticity of energy demand ☆. *Energy Policy*, *102*(April 2016), 549–568. https://doi.org/10.1016/j.enpol.2017.01.002

Lopez, N., & Espiritu, J. F. (2011). An approach to hybrid power systems integration considering different renewable energy technologies, *1*, 463–468. https://doi.org/10.1016/j.procs.2011.08.086

Lund, H., & Mathiesen, B. V. (2009). Energy system analysis of 100% renewable energy systems-The case of Denmark in years 2030 and 2050. *Energy*, *34*(5), 524–531. https://doi.org/10.1016/j.energy.2008.04.003

MEM. (2013). *THE UNITED REPUBLIC OF TANZANIA Revised Draft Energy Susidy Policy*.

MEM. (2016). Power System Master Plan: 2016 Update, (December).

Mikkola, J. (2017). Modeling and optimization of urban energy systems for large-scale integration of variable renewable energy generation, 170. Retrieved from https://aaltodoc.aalto.fi/bitstream/handle/123456789/24405/isbn9789526072654.pdf?sequence=1&isAllowed=y

Mutingi, M., Mbohwa, C., & Kommula, V. P. (2017). System dynamics approaches to energy policy modelling and simulation. *Energy Procedia*, *141*, 532–539. https://doi.org/10.1016/j.egypro.2017.11.071

Nakata, T., Silva, D., & Rodionov, M. (2011). Application of energy system models for designing a low-carbon society. *Progress in Energy and Combustion Science*, *37*(4), 462–502. https://doi.org/10.1016/j.pecs.2010.08.001

Neudoer, R. C., Malhotra, P., & Ramana, P. V. (2001). Participatory rural energy planning in India * a policy context, *29*, 371–381.

Neves, A. R. (2010). Energy sustainability indicators for local energy planning : Review of current practices and derivation of a new framework, *14*, 2723–2735. https://doi.org/10.1016/j.rser.2010.07.067

REFERENCES

OECD/IEA. (2014). Energy in Africa Today. *Africa Energy Outlook*, 13–25. https://doi.org/https://www.iea.org/publications/freepublications/publication/africa-energy-outlook.html

Peng, D., & Poudineh, R. (2016). *Sustainable electricity pricing for Tanzania*. Retrieved from http://www.theigc.org/wp-content/uploads/2016/08/Peng-Poudineh-2016-Working-Paper.pdf

Plain, N., Hingray, B., & Mathy, S. (2018). SC. *Renewable Energy*. https://doi.org/10.1016/j.renene.2018.07.036

Prasad, R. D., Bansal, R. C., & Raturi, A. (2014). Multi-faceted energy planning : A review, *38*, 686–699. https://doi.org/10.1016/j.rser.2014.07.021

Qudrat-Ullah, H. (2013). Understanding the dynamics of electricity generation capacity in Canada: A system dynamics approach. *Energy*, *59*(11), 285–294. https://doi.org/10.1016/j.energy.2013.07.029

Qudrat-Ullah, H. (2016). The Physics of Stocks and Flows of Energy Systems. https://doi.org/10.1007/978-3-319-24829-5

Reddi, K. R., Li, W., Wang, B., & Moon, Y. (2013). System dynamics modelling of hybrid renewable energy systems and combined heating and power generator. *International Journal of Sustainable Engineering*, *6*(1), 31–47. https://doi.org/10.1080/19397038.2012.689781

SETIS. (2016). Energy Systems Modelling, (13).

Sgouridis, S., & Csala, D. (2014). A framework for defining sustainable energy transitions: Principles, dynamics, and implications. *Sustainability (Switzerland)*, *6*(5), 2601–2622. https://doi.org/10.3390/su6052601

Situation, T. E. (2016). Tanzania (pp. 2013–2016).

Sterman, J. (2000). *Systems Thinking and Modeling for a Complex World*.

Tait, L., Mccall, B., & Stone, A. (2014). Energy futures modelling for African cities – selecting a modelling tool for the SAMSET project. Retrieved from http://www.africancityenergy.org/uploads/resource_27.pdf

REFERENCES

Terrados, J. Ã., Almonacid, G., & Hontoria, L. (2007). Regional energy planning through SWOT analysis and strategic planning tools . Impact on renewables development, *11*, 1275–1287. https://doi.org/10.1016/j.rser.2005.08.003

Thery, R., & Zarate, P. (2009). decision making structure proposal, 265–274. https://doi.org/10.1007/s10100-009-0091-5

Trancik, J. (2014). Back the renewables boom. *Nature*, 4–6.

Trappey, C. V., Trappey, A. J. C., Lin, G. Y. P., & Chang, Y. S. (2011). System dynamics evaluation of renewable energy policies. *Advanced Concurrent Engineering*, 133–140. https://doi.org/10.1007/978-0-85729-799-0_15

Varro, L. (2015). PROJECTED COSTS OF 2015 Edition Projected Costs of Generating Electricity , 2015.

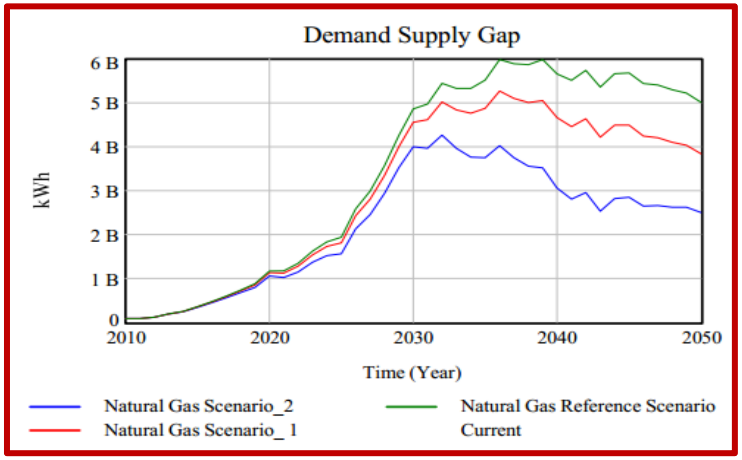
Vogstad, K. (2004). A system dynamics analysis of the Nor- dic electricity market : The transition from fossil fuelled toward a renewable supply within a liberal- ised electricity market. *System*, *1*(January).

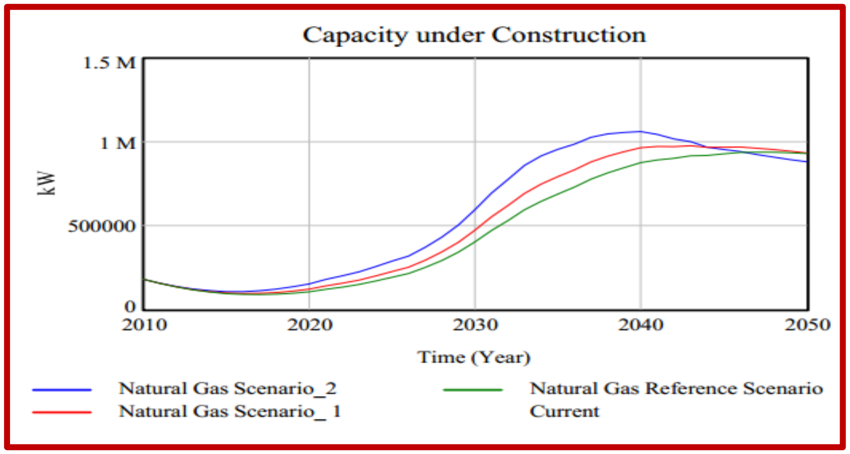
Zeng, H., Frenchman, D., & Ferreira, J. (2011). Integration of renewable energy with urban design based on the examples of the solar photovoltaics and micro wind turbines. Retrieved from http://dspace.mit.edu/handle/1721.1/69461#files-area

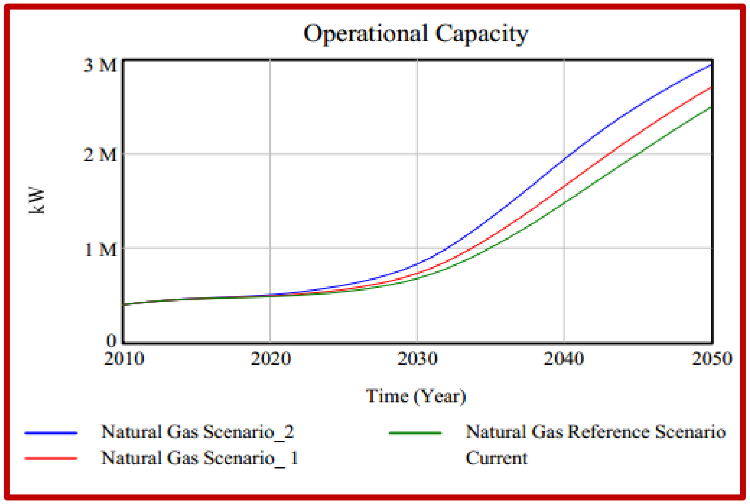
8 APPENDICIES

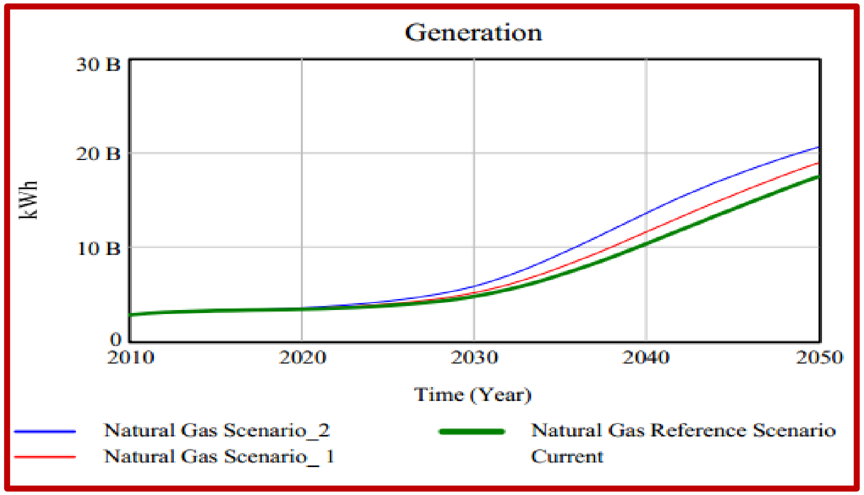
APPENDIX 1: Scenario Results of Auxiliary Variables (Explained in Section 5.3)

8.1.1 **Natural gas Curves**

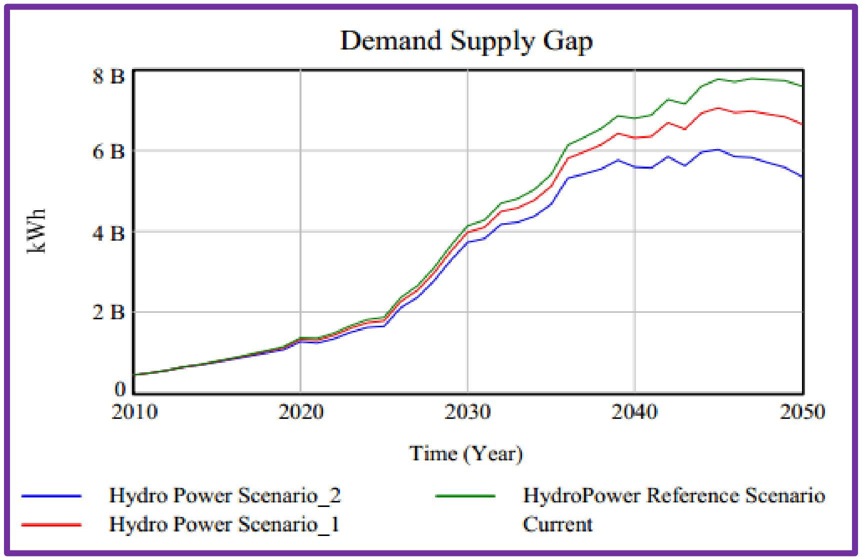


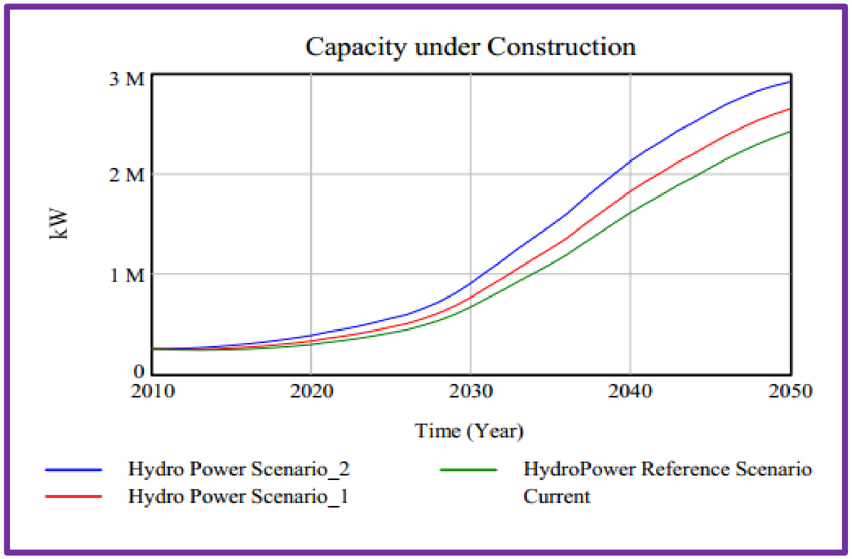


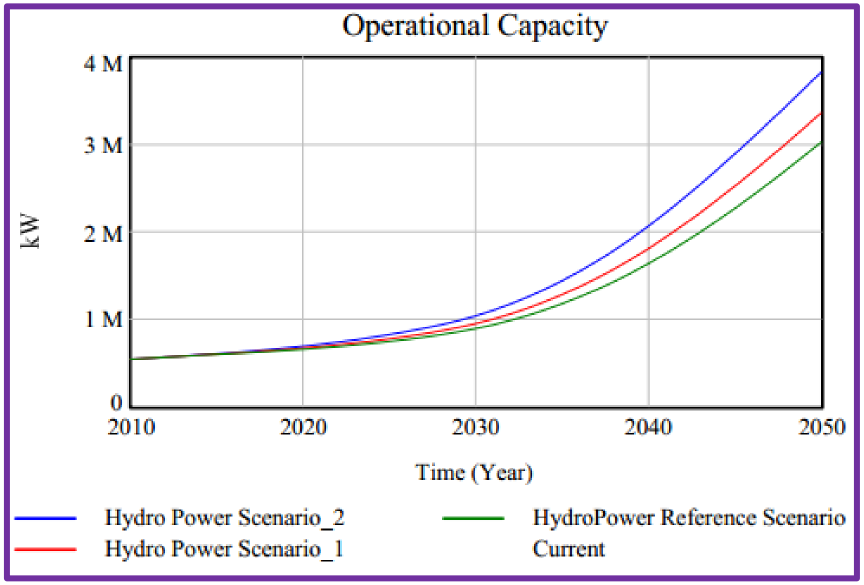


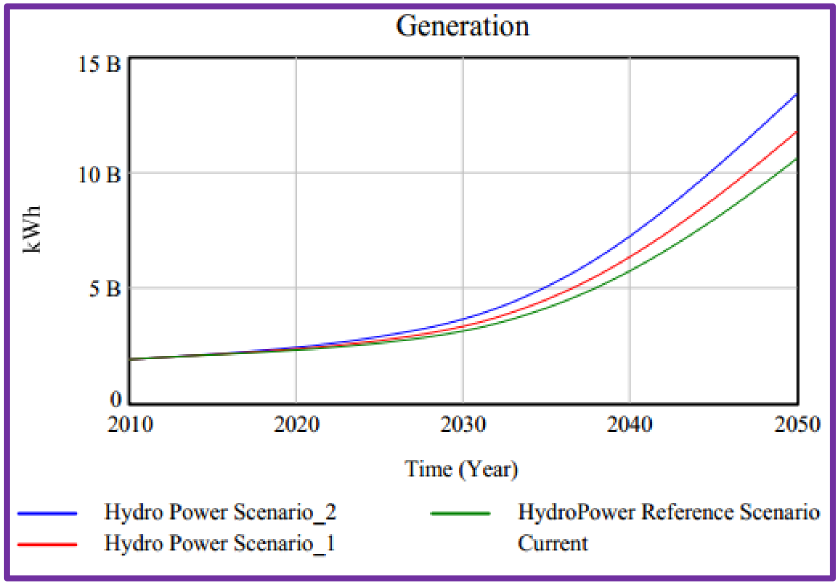


8.1.2 Hydro Power Curves

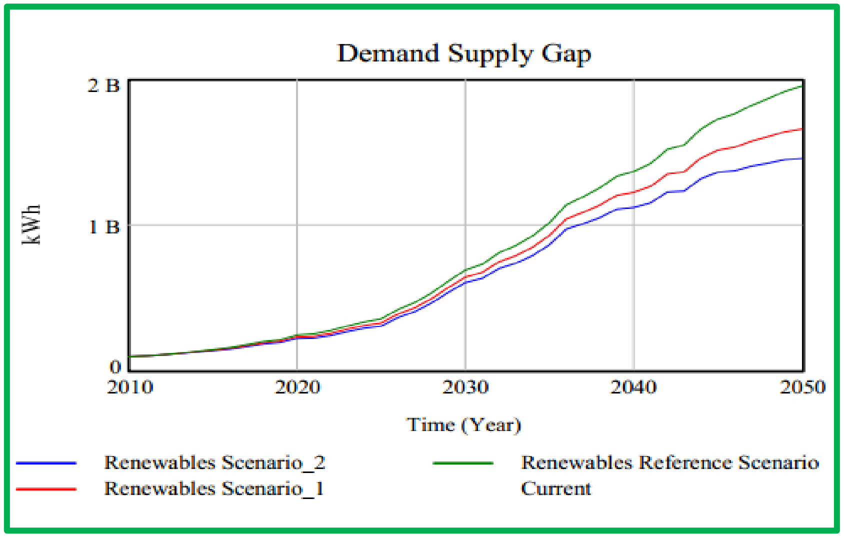


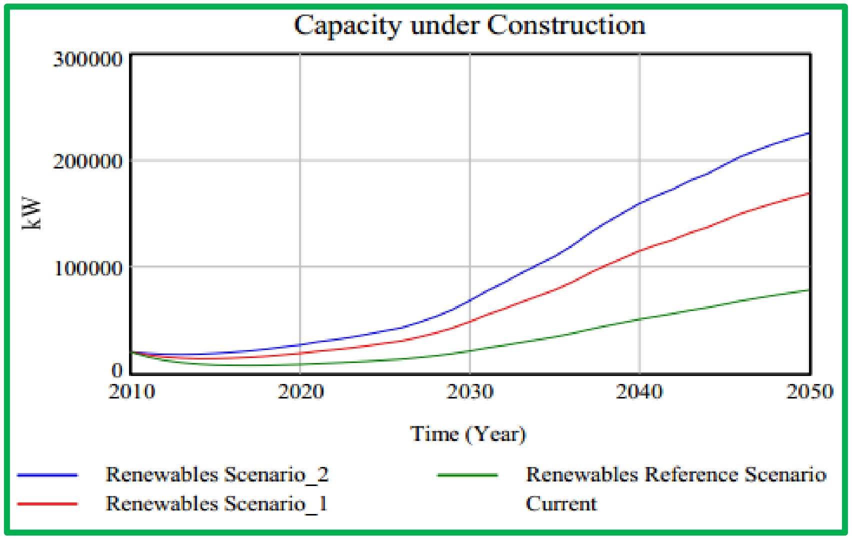


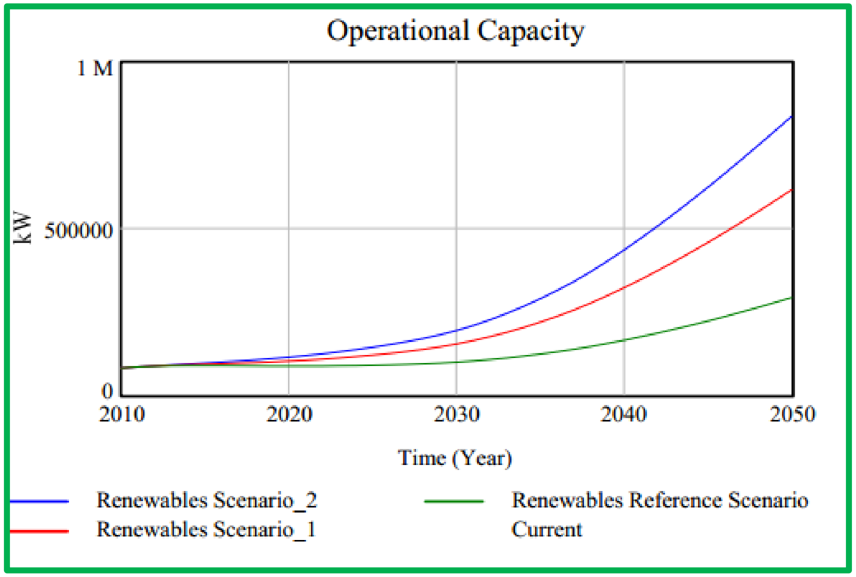


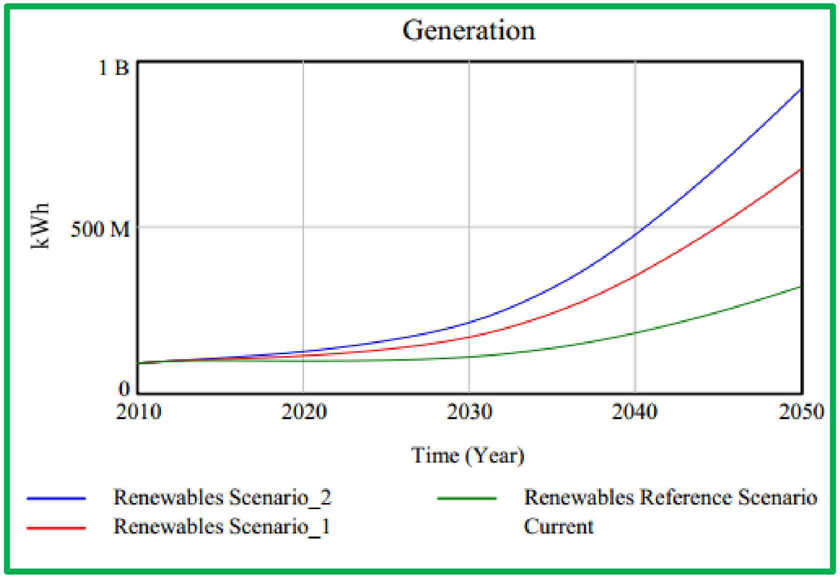


8.1.3 Renewables









APPENDIX 2: Research Grant justification

8.1.4 Research grant justification

BUDGET EXPENSES REPORT FOR MSC RESEARCH

Exchange Rates | **1.61 pounds(Airport Rate), 108 dinars**

	Group	***Explanation***	***Item***	***Payment methods***	***Expenses in Currency Used***	***Expenses in USD***
Transport to an from Algiers				Cash		30
Lodging in Algiers for flight connection				Cash		75
Transport	Transport to Lancaster:	No direct flights to Lancaster from Algiers. Flight taken to London Gatwick and train taken to Lancaster	Return Flight to London Gatwick Airport	Cash	70,000 dinars	648.1481481
			National Express bus from Gatwick to London Victoria Coach Station	Using Revolut Card	19 pounds	30.59
			Oyster card purchase for bus and train transactions	Using Revolut Card	20 pounds	32.2
			Return Train from from London Victoria Coach to London	Using Oyster Card	10 pounds	16.1
			Train from London Euston Station to Lancaster station	Using Revolut Card	80 pounds	128.8
			turn train from Lancaster station to London Euston (off peak tra	Using Revolut Card	100 pounds	161
			Bus to London Gatwick Airport from Victoria Coach Station	Using Oyster Card	25 pounds	40.25
	Transport to and from Lancaster University	3pounds round trip	20 days of working at University Campus	Using Oyster Card	60 pounds	96.6
Expenses relating to living and communications	Lodgings in UK	Lodgings and Bedding	Single room Lodging 40 Coulston Road, Lancaster, Lancashire, LA1 3AE	Cash	350 pounds	563.5
		Utilities	Gas, electricity, waste disposal and recycling, wifi, etc.	Cash	120 pounds	193.2
	Communication in UK	Giffgaff mobile subscription	Monthly subscription for mobile phone including mobile data	Using Revolut Card	80 pounds	128.8
	Data Expenses in Algeria	Ooredoo mobile subscription for	Monthly subscription for mobile phone including mobile data	Cash	14,000 dinars	129.6
	Meals	(5 pounds a meal)	Monthly meals	Cash	375 pounds	603.75
Research expenses	Data sets for modelling process		Data sets for modelling, datasets obtained from IEA	Using Revolut Card	120 pounds	193.2
	Printing and Miscellanaous					30
				Total Expenditure		**3100.767778** **3000**