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MODELLING SUSTAINABLE ENERGY TRANSITIONS FOR GHANA

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MODELLING SUSTAINABLE ENERGY TRANSITIONS FOR GHANA

Declaration

I, **Manjong Nelson Bunyui** 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.

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Date: 22-Sept-2018

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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:

Date: 10-Sept-2018

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Modelling Sustainable Energy Transitions for Ghana

Abstract

The transition to a sustainable energy system is constrained by two key factors: fossil resource depletion and the rapid adverse effects of CO2 emissions leading to climate change. This thesis uses systems dynamics to model the sustainability index of an energy resource termed "the energy return on energy investment (ERoEI)". The energy return on energy investment (ERoEI) is a dimensionless metric which defines the ratio of the 'net useful energy' return to the society to the energy consumed in the making the 'net useful energy' available. We employ the ERoEI to measure the sustainability of fossil and scale unlimited renewable resources (Wind and solar) in Ghana. Considering the dynamic evolution and stochastic behaviour of ERoEI, causal and feedback loops (systems dynamics) are used to model the interactions between the different intervening variables of the two sub systems under investigation: the fossil and the renewable sub system. Furthermore, a timeseries of dynamic evolution of ERoEI is developed for a period of 90 years starting from 2010 to 2100. 2010 is used as the incept year of the fossil fuel technology and as base year from which the modelling process starts and 2100 is considered as an end period of the modelling process.

The approach consists of evaluating for each sub system two key attributes termed the technological progression and the resource quality. The technology progression for fossils in Ghana is considerably faster than renewables but the rate at which the fossils degrade is also very high leading. The combined ERoEI for fossils (natural gas and oil) grows gradually from 2010 with a value of 1 and peaks at a 2026 with a value of 15. 2026 therefore corresponds to the year of maximum fossil production in Ghana, however, after 2026, the fossil ERoEI drops gradually as the ultimately recoverable resources continue to decrease until the value of ERoEI drops below 1 by 2040 indicating the fossil resources no longer yield net positive energy to the society.

Unlike fossils, renewables begin with a relatively low ERoEI, a value which is practically zero as there exist no significant renewable energy plants in Ghana now. However, our model shows if the government of Ghana continues to develop renewables, the ERoEI of renewables will grow steadily from 0 in 2020 to a value of 15 by 2030 and this value is maintained until the end of the simulation period 2100. By a simple comparative assessment of the ERoEI of the two sub systems, it is more appropriate for the government of Ghana to plan integration of renewables as quick as possible as fossil resource depletion is eminent as from 2026. Therefore, renewables are the better energy resource for the Ghanaian economy looking at the value of the ERoEI and the technical potentials of the resources available unlike fossils which are on the rise but will soon deplete.

La Transition des énergies Durables pour le Ghana

Résumé

La transition vers un système énergétique durable est caractérisée par deux facteurs clés : l'épuisement des ressources fossiles et les effets rapides des émissions de CO2 conduisant au changement climatique. Cette thèse utilise la dynamique des systèmes pour modéliser l'indice de durabilité d'une ressource énergétique appelée « retour énergétique sur investissement énergétique (ERoEI) ». Le retour d'énergie sur l'investissement énergétique (ERoEI) est une mesure sans dimension qui définit le rapport du rendement de « l'énergie utile nette » à la société à l'énergie consommée pour rendre « l'énergie utile nette » disponible. Nous utilisons l'ERoEI pour mesurer la durabilité des ressources fossiles et des ressources renouvelables à échelle illimitée (éolienne et solaire) au Ghana. Considérant l'évolution dynamique et le comportement stochastique d'ERoEI, des boucles causales et de rétroaction (dynamique des systèmes) sont utilisées pour modéliser les interactions entre les différentes variables intervenantes des deux sous-systèmes étudiés : le sous-système fossile et le sous-système renouvelable. De plus, évolution dynamique d'ERoEI est développée pour une période de 90 ans de 2010 à 2100. 2010 est utilisée comme année de référence de la technologie des combustibles fossiles et comme année de référence à partir de laquelle le processus de modélisation commence et 2100 est la fin du processus de modélisation.

L'approche consiste à évaluer pour chaque sous-système deux attributs clés nommés progression technologique et qualité de la ressource. La progression de la technologie pour les fossiles au Ghana est considérablement plus rapide que celle des énergies renouvelables, mais la vitesse à laquelle les fossiles se dégradent est également très élevée. L'ERoEI combiné pour les fossiles (gaz naturel et pétrole) augmente progressivement à partir de 2010 avec une valeur de 1 et culmine à 2026 avec une valeur de 15. 2026 correspond donc à l'année de production maximale d'énergie fossile au Ghana, mais après 2026, le Les ERoEI fossiles diminuent progressivement au fur et à mesure que les ressources récupérables continuent à diminuer jusqu'à ce que la valeur d'ERoEI tombe en dessous de 1 d'ici 2040, indiquant que les ressources fossiles ne donnent plus d'énergie positive nette à la société. Contrairement aux fossiles, les énergies renouvelables commencent avec un ERoEI relativement bas, une valeur qui est pratiquement nulle, car il n'existe actuellement aucune usine d'énergie renouvelable significative au Ghana. Cependant, notre modèle montre que si le gouvernement du Ghana continue à développer les énergies renouvelables, l'ERoEI des énergies renouvelables augmentera progressivement de 0 en 2020 à une valeur de 15 d'ici 2030 et cette valeur est maintenue jusqu'à la fin de la période de simulation l'année 2100. Par une simple analyse comparative de l'ERoEI de ces deux sous-systèmes, il est plus approprié que le gouvernement du Ghana planifie l'intégration des énergies renouvelables aussi rapidement que possible car l'épuisement des ressources fossiles est évident à partir

de 2026. Par conséquent, les énergies renouvelables sont la meilleure adaptée pour l’économie en regardant la valeur de l'ERoEI et les potentiels techniques des ressources disponibles contrairement aux ressources fossiles qui sont en hausse mais vont bientôt s'épuise

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List of Abbreviations

GDP: Gross Domestic Product

EROEI: Energy Return on Energy invested (EROEI)

TWh: Tera-Watts hours

MMCF: million cubic feet

TP: Technical Potential

URR: Ultimately Recoverable Resource

GWh: Giga-Watt hours

TPED: Total primary energy demand

TPES: Total primary energy supply

UNFCC: United Nations Framework Convention on Climate Change

IPCC: Intergovernmental Panel on Climate Change

Toe: ton of oil equivalent

INTRODUCTION

1.1 Background

The current global energy system is characterized by a series of dynamic interactions, stochastic behaviour as well as climate change constraints as a result of the excess greenhouse gas (GHG) emissions. The world's total population currently estimated at 7.3 billion people in 2018 is expected to increase to 11.3 billion people by the end of the century (Heilig, 2017) and the global energy requirements is expected to increase to meet the rapidly growing population. As the demand for energy continues to increase with the increasing population, non-renewable energy resources (fossil) are expected to deplete rapidly and scale limited renewables (hydro) will face tremendous reduction in the resource quality. Also, the externalities raised by excess deployment of fossil fuels will increase tremendously posing serious environmental hazards to the global ecosystem. These therefore call for a sustainable energy transition towards an environmentally friendly and constantly available energy resource (scale unlimited resources).

Africa forms a vital and an indispensable part of the energy transition process as a result of its rapidly growing population expected to reach 2.5 billion by 2050 and 4.4 billion by 2100 accounting for 39% of the total world's population by that time (Heilig, 2017).The energy demand for Africa (especially countries south of the Sahara;Sub-Sahara Africa) is expected to grow rapidly as Africa aspires for a prosperous continent based on inclusive growth and sustainable development as highlighted in the African Union Agenda of Vision 2063(African Union Commission, 2015). As energy and GDP bear a strong positive correlation, the energy demands of Africa is expected to grow rapidly for Vision 2063 to be achieved.

Africa is a growing continent with a lot of potentials, and the continent with the least greenhouse gas emissions, but should Africa go through the same path as Europe, America and China or should Africa make use of the opportunities and develop a sustainable energy system? While advocates of a continuous use of fossil employ the concepts of energy for development arguing that for Africa to develop, it is practically impossible for dependence on renewables to support huge energy demands, advocates for a sustainable transition and energy system development argue that, huge dependence on fossils by a growing continent like Africa will render the SDG goal 7 and global conventions set out by the United Nations Framework Convention on Climate Change (UNFCC) and the Intergovernmental panel on climate change (IPCC) unachievable. The question of a sustainable energy transition in Africa (especially sub-sahara Africa) is therefore of interest to the entire world and not just Africa.

In reality, sub-Sahara Africa has better opportunities towards a sustainable energy transition due to the following.

- Energy systems are still in the process of development
- Renewable energy resource potential especially solar is high in Africa
- Energy requirements and energy intensities per capita are still low compared to more developed nations like Europe, America and Asia.

A country which represents the three points listed above is Ghana, a country with a significant economic development and stands out as a model for many countries in Sub-Sahara Africa. However, the use of fossil in Ghana has become dominant with the government's quest to achieve economic development and increase the social welfare of its citizens. There has been rapid construction of thermal plants for electricity generation and the country has also started exploitation of its fossil resources (oil and gas). Fossil energy is therefore contributing a significant share in the country's energy mix. As the country's fossil resources will eventually deplete (since fossil is non-renewable) and climate constraints intensify, the quest to model and explore future scenarios of the behaviour of the Ghanaian Energy system becomes inevitable and the transition to a sustainable energy system becomes undisputable.

1.2 What is a sustainable energy transition?

Sgouridis & Csala (2014), defined a sustainable energy transition as: a controlled process that leads an advanced, technical society to replace all major fossil fuel primary energy inputs with sustainable renewable resources while maintaining a sufficient final energy service level per capita. This makes a sustainable energy transition not only a process of phasing out fossil but also includes creating renewable energy systems that can support the economy's energy demands without any shortages in the supply. Building up sustainable energy systems requires investment in terms of energy requirements (energy investments) and consequently monetary requirements (financial investments). In mapping out transitions, an important consideration is the energy use per capita which should increase over time or at the worst stay constant. As energy resources vary from one geographic location to the other, a suitable approach to ensuring sustainable energy transitions is modelling how much energy is required to build up a sustainable energy system within a given country.

1.3 Motivation

It has been argued by many researchers that, for a society to achieve a high cultural, economic and educational richness, it must have at its disposal a large quantity of energy resources with sufficiently high net energy, meaning, complex societies need a high Energy Return on Energy Invested built on large primary energy base (King & Hall, 2011). Fossil energy resources have historically very large values of EROEI, but however, these values are on an increasing decline calling for more reflections on the depletion of fossil and the future of renewables.

SET studies have been increasing gaining attention in the years. Sterman (1981) was the first to critically analyze the transitions model of the US energy economy in his work "the economy transition and the economy: A system dynamics approach" where he developed an integral framework to evaluate the effects of depletion and rising energy prices on the economic growth, inflation and other key economic and energy indicators. Other similar studies include those of Dale (2010) of "Global Energy Modelling: A biophysical Approach (GEMBA)" and Csala (2016) of "A data-driven dynamic net-energy analysis of global and national sustainable energy transition". All these works seek to address SET on a global or scale or across a very large geographic area.

As concerns Africa, most energy planning models are basically Economic Models generally Computable General Equilibrium models (CGE) which are developed based on flows of monetary value between sectors of an economy. The outputs of interest of such models are usually cash flows, prices and quantities of goods and services, tax revenues, consumer price, etc.…(Chamberlain & Duquette, 2012). As climate constraints and resource depletion continues to become significant, a more informative approach to modelling transitions in Africa becomes crucial. This thesis therefore is motivated by the Net Energy Analysis approach (Sgouridis, Bardi, & Csala, (2015), Csala, (2016), Raugei et al., (2017)) as a nouvelle approach in modelling transitions to sustainable energy in Sub-Sahara Africa using Ghana as a case study so as to develop sufficient insight to shape policies and actions by energy planners through national energy plans.

The thesis is motivated by the general energy scenario in Sub-Sahara Africa, however, Ghana is used as case study as it sets a good pace of economic development for other Sub-Sahara African countries.

As the increasing population continues to increase energy demand needs, the challenge of reducing the fossil consumption in Sub-Sahara Africa is of huge benefit to the ecosystem and to these countries. The use of fossil fuel has been greatly discouraged by advocates of sustainable ecosystems (UNFCC, IPCC, UNEP), however, many countries still use fossil fuel because they have no clear vision of the long-term benefits of renewables. The thesis takes an approach which advocates for the use of renewables by demonstrating the long-term benefits of renewables over fossil in Ghana rather than a strong disapproval of the use of fossils. It's in this vein the thesis employs the energy return on energy investments (ERoEI).

This thesis will therefore develop concepts, methodologies and insights on how EROEI can be used as a key metric by policy makers and national energy planners in planning national sustainable energy systems. The thesis fits into goals 7, 11 and 13 of the UN Sustainable development goals and supports the policies and conventions of the UNFCC and the IPCC

Figure 1-1:Three key SDG Goals this dissertation seeks to address

1.4 Research Questions

Evaluating the energy return on energy investment (ERoEI) on a national level is expected produce results to predict and plan the energy system for such a country. However, important consideration to make in such an evaluation is the extend of the boundary to which the energy system is defined to avoid extended boundaries (for example, considerations on whether energy imports and exports will be part of the energy system or not). Defining this system boundary is not a so easy process and requires a lot of diligence as the whole results of the study depend on the precision and concision of the boundaries of the system. Raugei et al.,(2017) explained that in order to avoid confusion and remain meaningful for energy policy, EROEI calculations should therefore always be associated with an explicit objective. In the case of Ghana, our system boundary will comprise of a conventional energy system, however, we will exclude the following:

- Energy imports and exports (net energy imports)
  - Though net energy imports for Ghana is evaluated at -4%[1] (Energy Commission-Ghana, 2016) the inclusion of net energy imports within this system raises complexities for the modelling process far above the scope of this thesis.
- Externalities of fossil use and carbon tax.
  - The model developed during in this thesis advocates for renewables by showing the intrinsic advantages associated with deployment of renewables. As such the externalities associated with fossil fuel use will not be considered.

The research questions which this study will seek to answer in assessing the sustainable energy

[1] Ghana exports more energy than it imports, therefore the net energy imports is negative

transitions will be:

- How can a time series of ERoEI be developed for different energy resources in Ghana using system dynamics?
- Does Ghana need to transit its current energy system?
- How does these ERoEI values define a sustainable energy transition for Ghana?
- Can the information we obtain from ERoEI support developments and investments in renewables in Ghana?

The thesis assumes the following:

- Energy demand in Ghana is an exogeneous variable in our model, as such, people will continue to need energy even if the resources needed to provide this energy are completely depleted and price needed to procure the energy is not a limiting factor.
- An energy resource depletion forces a shift to the remaining alternative resources available.

Assessing SET and the different energetic metrics of ERoEI and net energy for Ghana is not linear science or should not be if considered as one. The dynamic evolution and stochastic behaviour of energy systems make their study very sensitive. Energy systems as well as other biophysical systems are mostly complex and require a deep reflective view of the research questions and overall objective if they are to produce results that are accurate. A more reflective view of systems thinking as described by Lewis Thomas in Sterman's Book titled "business dynamics" states that:

> "When you are confronted by any complex social system, such as an urban center or a hamster, with things about it that you're dissatisfied with and anxious to fix, you cannot just step in and set about fixing with much hope of helping. This realization is one of the sore discouragements of our century . . . You cannot meddle with one part of a complex system from the outside without the almost certain risk of setting off disastrous events that you hadn't counted on in other, remote parts. If you want to fix something you are first obliged to understand. . .the whole system. Intervening is a way of causing trouble." (J. D. Sterman, 2000)

Our study will align with the system dynamics philosophy, "everything is connected to everything else". The sustainable energy transition for Ghana will therefore be a system dynamics approach employing the concepts of causal loops and interactions between intervening variables is the most dynamical way possible. The system variables and the model dynamics will be developed in a setting to allow comparative assessments of the ERoEI of the different energy resources in Ghana.

1.5 Objectives

The study offers an energetic approach for national energy planning with objectives of creating a SET. Since former transitions from organic to mineral have spanned over decades and the present transition doesn't have to reflect what happened in the past, it is therefore a practical step to start planning the next SET. Since migrating to a SET requires energy investments, the objective of the study is to analyze how much energy is required to build up a SET. By analyzing the ERoEI, it is possible to show how the values of the ERoEI will change for a given selected resources with time. For an energy system to be termed sustainable, the ERoEI should increase over time (depicting an inexhaustible supply of resources) or at the worst stay constant. Energy resources will a decreasing ERoEI show that the resources are depleting or they available resources are becoming less efficient. Energy resources which show an increasing ERoEI characterize a sustainable transition and are therefore recommended. Evaluating this energetic metric for Ghana will present deep insights into the SET pathways for national energy planners and policy makes. The dissertation therefore seeks to achieve the following:

- Provide information on the technological progression and resource depletion of the different energy resources in Ghana.
- Show how ERoEI metric can be used to assess among different technologies which ones are sustainable and preferential according to the trends of the ERoEI.
- Provide a timeseries information on the annual production and the net energy available for each energy resource to meet the demands of Ghana.
- Incorporate ERoEI and net energy as key metric in energy planning studies.

1.6 Relevance of an energy transition study in Ghana

Ghana is heavily dependent on hydro and fossil for electricity production and a huge use of traditional biomass for cooking. Though hydro is a renewable energy resource, it is scale limited and Ghana has used approximately 80% of its hydro potential, this situates the country in a position where it can no longer use hydro to meet the growing energy demand needs of the country. As fossil will eventually deplete and hydro cannot meet the energy needs, the dynamics of introducing new energy resources into the energy mix will be of great importance to Ghana. Understanding concepts of ERoEI will therefore be a solid factor in renewable energy integration and a sustainable energy transition.

LITERATURE REVIEW

Energy systems are best understood as socio-technical arrangements with a strong interrelation of technological and social elements such as institutions, regulations, cultural values, social practices as well as interests, expectations and relationships of the actors involved (Rohracher, 2008). An energy system comprises of the primary energy resources, the energy conversion equipment and process, the second energy obtained, the final energy as well as the human interaction involved in the process of exploiting, transforming and distributing energy.

2.1 Energy System Analysis

There exist different methods of analyzing energy systems, however, the main goal of the process is to understand how the complexities associated with the system so as to properly plan, utilized and optimized use of energy resources for the development of societies/economies with the least possible external cost.

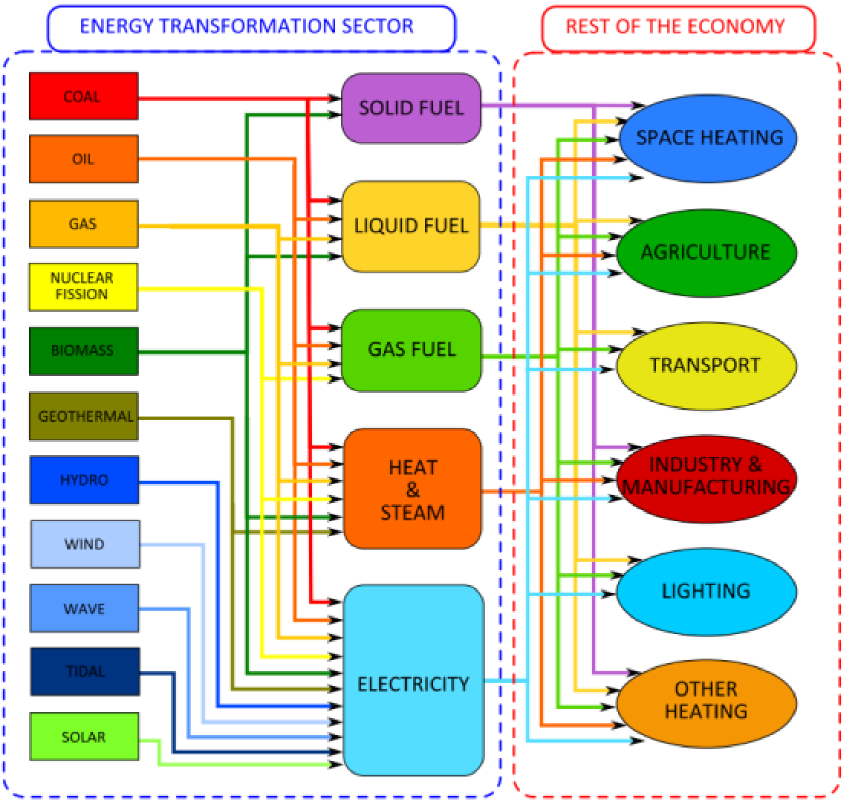


Figure 2-1:Model of Energy-Economy from resource to end use

Source (Michael Dale, 2010)

The complexity of assessing energy systems are due to following attributes (Howells, 2013):

- Energy is strategic
- Energy is integrated
- Energy is intra-grated
- Energy technologies and systems are dynamic

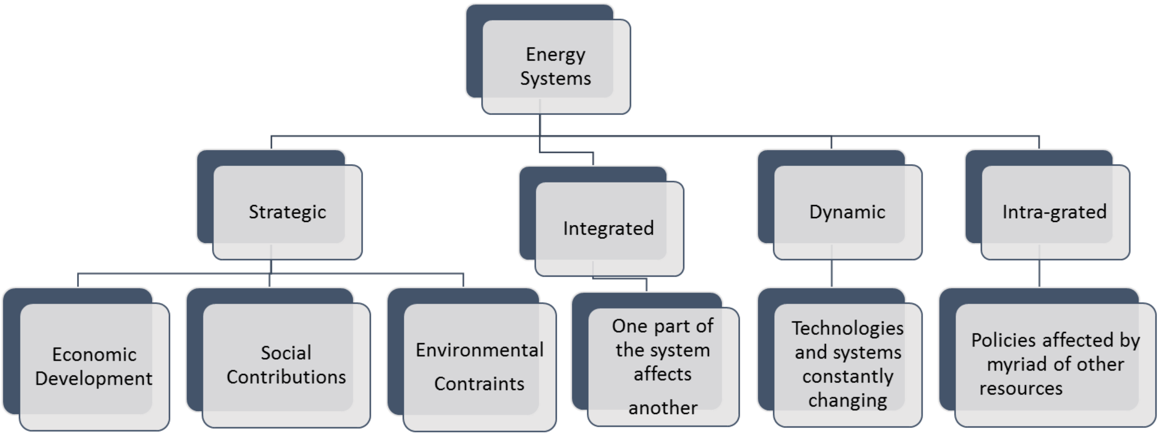


Figure 2-2: Energy System Analysis

As energy systems present a wide range of socio-technical attributes, attempts at understanding such high degrees of complexities are usually done through energy modelling. Energy models are an abstraction of the real world which simulates, plans and characterizes the energy system, and its interaction with the broader economy. Modelling energy systems is an applied science and therefore not always exactly right but atleast, the models created are useful. Neils Bohr's quote "Prediction is difficult, especially about the future" is therefore is the process of modelling future energy systems. The quote below explains the importance of personal judgment in the modelling process.

> "*As an individual looking to understand others' modelling studies, the safe course of action is to take one's own judgment, rather than trusting entirely the authors or reviewers – of course some authors or forms of publication will be worthier of trust than others. One must also understand that over time knowledge develops, so what was deemed best practice some years ago might not remain thus"*(Chris Dent,)

Energy modelling approaches are classified into three main groups (Howells, 2013):

- Bottom Up energy systems models
- Top down economic levels and
- Different levels of integration of the first two.

2.1.1 Bottom Up Energy Systems Models

The engineering approach is to develop bottom-up models with thorough descriptions of technological aspects of the energy system and how it can develop in the future. Energy demand is typically provided exogenously, and the models analyse how the given energy demand should be fulfilled in a cost-optimal fashion. The interplay between energy and other production factors to create economic growth as captured in production functions, and opportunities to make changes in fuel mixes are described by elasticities of substitution (Helgesen, 2013). According to Herbst et al (2012), bottom up energy models usually cannot consider macroeconomic impacts of energy or climate policies or related investments. They do not consider transaction costs which are implicitly covered by top-down models. Their technological detail and transparency considering technological progress and the diffusion of new energy technologies make them unsuitable for very long-term energy demand and supply projections in technology areas with re-investment cycles of less than 20 years (e.g. future generations of a new technology may be quite different from its present type). Bottom up energy models can be further divided into : optimisation models, simulation models, accounting models and multi-agent models.(Herbst et al., 2012). However, the thesis is not based on any of these models and therefore not much literature will be reviewed on them, but it's worth noting that the MARKAL model, MESSAGE, ENERGYPLAN and LEAP both fall under this group of energy systems modelling approach.

2.1.2 Top down Energy-Economy Models

Top-down models use aggregated market data to predict the overall economic effect of a policy. They range from simple identity-type models to complex models that capture inter-sectoral transactions through an input/output table, with some portraying full equilibrium throughout the economy(Rivers & Jaccard, 2005). Top down energy economy models are divided into four main types.(Herbst et al., 2012)

- Input-output models
- Econometric models
- Computable General Equilibrium Models (CGE)
- System Dynamic Models.

Table 2-1 below gives the definition of the different top down models.(Rivers & Jaccard, 2005)

Table 2-1: Different Energy Modelling Methodologies

Model	Definition and Examples
Input-Output Model	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.

Econometric Models	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 models (CGE)	based on microeconomic theory and calculate how both prices and activities in all sectors change in order to reach a general equilibrium in the economy. Like the first group, these models also build on the input-output data from national accounts
System Dynamic Models	have predefined rules for the behaviour of different actors in the model and are able to make complex non-linear simulations on this basis.

2.1.3 Systems Dynamic Modelling

System dynamics is also a rigorous modeling method that enables us to build formal computer simulations of complex systems and use them to design more effective policies and organizations. System dynamics is grounded in control theory and the modern theory of nonlinear dynamics. There is an elegant and rigorous mathematical foundation for the theory and models we develop. System dynamics is also designed to be a practical tool that policy makers can use to help them solve the pressing problems they confront in their organizations (J. D. Sterman, 2000). System dynamics has very broad area of application. It employs a top-down view for modeling of system. It identifies the main variables of the system and causal relations among them. Groups of causal relations among variable form the structure of feedback loops. These structures drive the behavior of the system.(Kooshknow, 2013)

The reference literature for System dynamics and system thinking is John Sterman's book: "Business Dynamics: Systems Thinking and Modelling for a Complex World" which covers a wide range of applications from transportation, supply chain, automobile and energy. An extract from Sterman's literature:

> "System dynamics is a method to enhance learning in complex systems. Just as an airline uses flight simulators to help pilots learn, system dynamics is, partly, a method for developing management flight simulators, often computer simulation models, to help us learn about dynamic complexity, understand the sources of policy resistance, and design more effective policies. But learning about complex dynamic systems requires more than technical tools to create mathematical models. System dynamics is fundamentally interdisciplinary. Because we are concerned with the behavior of complex systems, system dynamics is grounded in the theory of nonlinear dynamics and feedback control developed in mathematics, physics, and engineering. Because we apply these tools to the behavior of human

> as well as physical and technical systems, system dynamics draws on cognitive and social psychology, economics, and other social sciences. Because we build system dynamics models to solve important real-world problems, we must learn how to work effectively with groups of busy policy makers and how to catalyze sustained change in organizations”

To better understand and represent the nonlinear relationships in the energy-economy, causal loop diagrams are used. By graphical notation representing the elements of the energy-economy, it is clear to map and mathematical formulate the relationships existing between these elements. In a system dynamics formulation, the elements are usually referred to as variables or parameters while the arrows showing the relationships between these variables are called loops. More formally, a feedback loop is a closed sequence of causes and effects, that is, a closed path of action and information. The reason for emphasizing feedback is that it is often necessary to consider feedback within management systems to understand what is causing the patterns of behavior (Kirkwood, 2013).

Mutingi, Mbohwa, & Kommula, (2017) defined the following complexities associated with energy systems dynamics modelling.

- *Energy System Uncertainties*
    - Energy sector is faced with unprecedented changes which are technological innovations, energy price fluctuations or even human interventions. These constantly changing variables make it very difficult for to formulate effective policies.
- *Nonlinear relationships between system variables*
    - The relationship between energy system variables are 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(Mutingi et al., 2017)
- *Time Delays*
    - Time delays are very common phenomenon of energy projects. Therefore, in modelling energy scenarios and policies, system dynamics accounts for the delays which occur in projection completion and the delays which occur for policies to be set and implemented.

As already discussed, SD is a mathematical and methodology modelling technique for framing, understanding and discussing complex issues and problems over time using stocks and flows, internal feedback loops and time delays (Capellán-pérez, 2017)

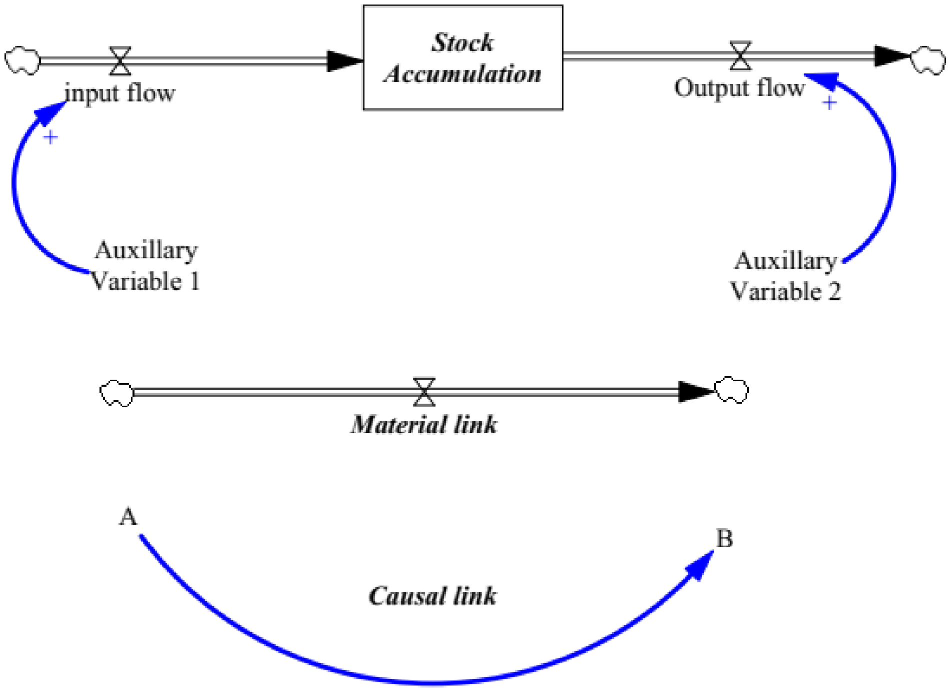


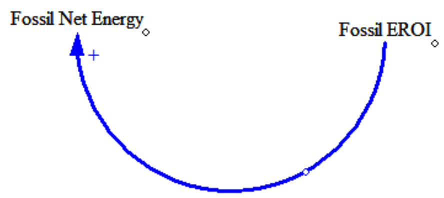
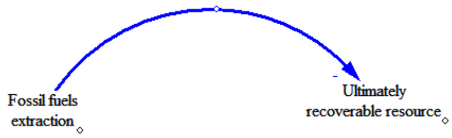
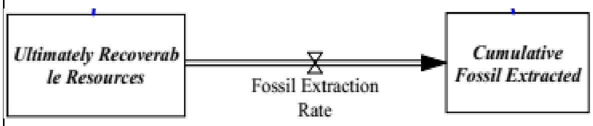
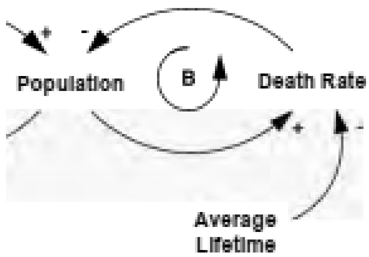
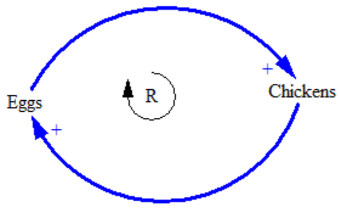
Figure 2-3: SD Simplified Modified Showing Causal links, stocks and flows

The causal relationship between two variables are defined using positive (+) and (-) signs. A positive sign means the two related variables change in the same direction (increase simultaneously or decreased simultaneously) while a negative sign means the change between the two variables is opposite; when one increases, the other decreases and vice versa.

The SD terminologies are summaries below as this thesis is based on the usage of this approach.

Table 2-2: Systems Dynamics diagrammatic representation in Vensim

Item	Explanation	Diagram
Variables	All entities and physical elements used in system dynamics are referred to as variables. The maybe monetary, energy units, population, etc..	

Positive Causal link	If there exist a positive causal link between two variables of the system, the two variables will change in the same direction. i.e,	
Negative Causal links	The change between the two variables are in opposite directions. Tail variable increases and head variable decreases and vice versa.	
Stock and flows	Stocks and flows are the main concepts of SD. Stocks are accumulating variables while flows are rate variables.	
Balancing loops	Loops that counter a change in the opposite direction. Referred to as negative loops, the try to maintain the system in a stable position.	
Reinforcing loops	Reinforcing loops are loops where the system reactions to push the loop further towards its original direction. These loops lead to increase or decline	

2.1.4 Energy Transition Models Developed Using System Dynamics

Unlike the many existing conventional models which are price based, system dynamic modelling of energy systems focuses on physical resource conformance with the laws of thermodynamics. This is because, the use of a price based analysis within economic models has three main limitations:firstly, the problem of price forecasting' over long periods of time; secondly, that production costs are not influenced by energy prices and; thirdly, that not all important features may be captured by price (Michael Dale, 2010).

2.1.4.1 Energy Transition and the Economy-John Sterman

John Sterman in his thesis, “the energy transition and the economy” used system dynamics to developed a framework of policies for the US economy. His model was designed to provide a vehicle for understanding the role of energy in the economy and for evaluating the microeconomic consequences of energy policies. His model represented a detailed physical behaviour and decision making structures of the various sectors of the economy, including energy policy initiatives, subsidies for energy production and endogenously generated the major and economic aggregates such as GNP, consumption, investment, real and nominal wages, rates of inflation and energy production. (D. Sterman, 1981).

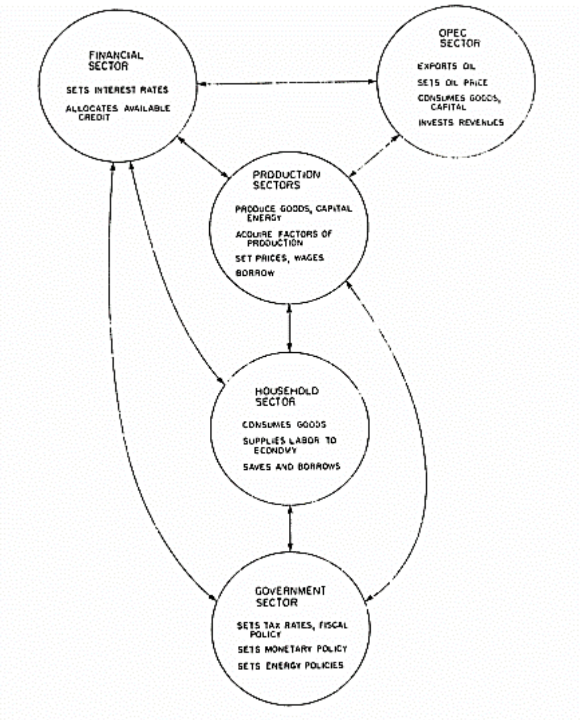


Figure 2-4: An overview of Sterman's Model

2.1.4.2 GEMBA Model-Michael Dale

Michael Dale developed the GEMBA (Global Energy Modelling: A Biophysical Approach) model based on a system dynamics methodology utilizing stocks and flows, feedback loops and time delays to capture the behaviour of the global energy-economy system. The core of the GEMBA model was constituted of the description of a dynamic EROEI function over the whole production cycle of an energy resource from initial development, through maturation to decline in production, in the case of non-renewable resources, or to the technical potential in the case of renewable resources.(Michael Dale, 2010)

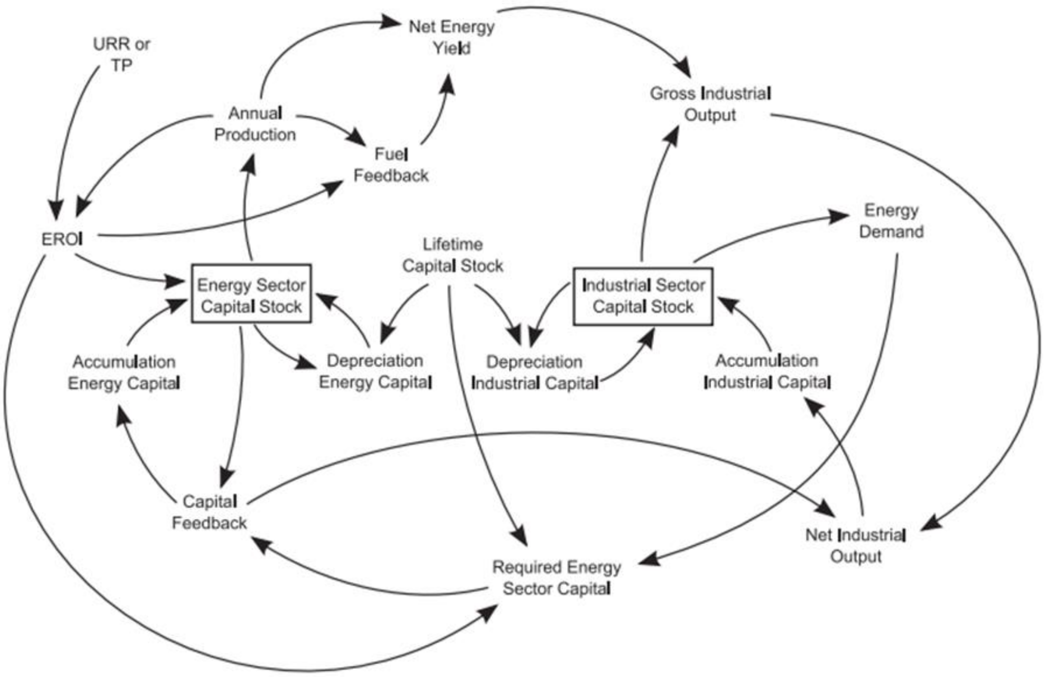


Figure 2-5: Causal Loop of the Global Energy Economy

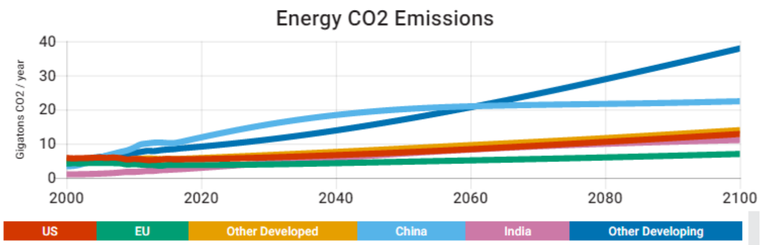
Source:(M. Dale, Krumdieck, & Bodger, 2012b)

Dale's dynamic EROEI function was defined as a product of two attributes: the resource depletion or resource quality (for renewables) and the technological progression. The resource depletion was characterised by how much exhaustible resources were being used and the technological progression was characterised by how much learnings and economies of scales influenced efficiency. A detailed explanation of these two parameters will be discussed later. Dale's development of the GEMBA project has served as a key methodology for other biophysical modelling approaches of the energy economy.

The results of the GEMBA model were a prediction of the global net energy up to the years 2200. The net energy was defined in the GEMBA model as the difference between the output energy available for production to the society and the input energy used to make the output energy available. Detail calculations of the net energy will be explained later in this dissertation.

2.1.4.3 C-Roads and En-Roads

C-Roads (Climate Rapid Overview and Decision Support) and En-Roads (Energy – Rapid Overview and Decision-Support) are two system dynamic models developed by Ventana systems and are used to model global climate and energy scenarios. The C-ROADS (Climate Rapid Overview and Decision Support) model is designed to address these issues and build shared understanding of climate dynamics in a way that is solidly grounded in the best available science and rigorously nonpartisan, yet understandable by and useful to nonspecialists, from policymakers to the public. (J. Sterman et al., 2012). The En-Roads is designed to provide a rapid, broad-brushstroke, rigorous overview of the dynamics of global energy supply and demand scenarios and the resulting climate change impacts (Jones & Interactive, 2012). The C-Roads is developed based on the work of Todd Fincannon while the En-Roads is based on the PhD thesis of John Sterman and Tom Fiddaman. The C-Roads and the En-Roads are both global modelling softwares and therefore cannot be used to model national energy supply scenarios and climate change. However, they do produce interesting results that help policy makers draw interesting conclusions.



	Emissions Peak Year	Reductions Begin Year	Annual Reduction Rate	Prevent Deforestation	Promote Afforestation
US	2100	2100	0%	0%	0%
EU	2100	2100	0%	0%	0%
Other Developed	2100	2100	0%	0%	0%
China	2100	2100	0%	0%	0%
India	2100	2100	0%	0%	0%
Other Developing	2100	2100	0%	0%	0%

Figure 2-6: C-Roads Output

Source: (C-Roads, 2018)

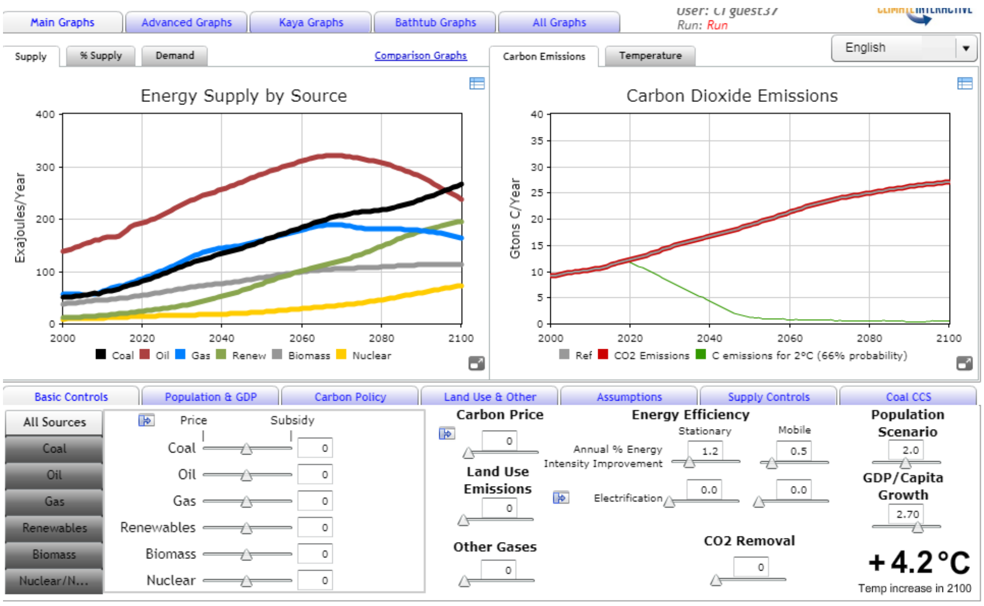


Figure 2-7: En-Roads Simulation Output Source:(En-ROADS, 2018)

2.1.4.4 NETSETS- Dénes Csala

Csala developed a data driven system dynamic model called NETSET (Networked Sustainable Energy Transition) (Csala, 2016) which follows a net energy analysis methodology similar to the GEMBA. However, the NETSET (Http://netset.csaladen.es/, 2018) has been programmed as a comprehensive, user friendly web interface which can be accessed remotely. The results of his study have a deep and give more clarity to the global energy system, the results of the net energy analysis obtained show net energy inflows and outflows for all the countries of the world.

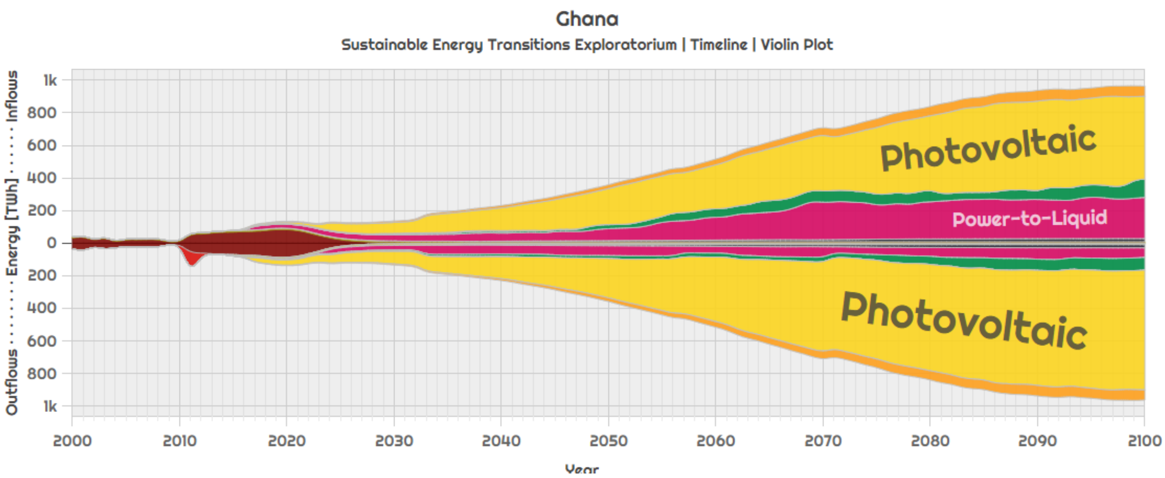


Figure 2-8: NETSET Explorotorium for Ghana

2.2 Sustainable Energy Transitions

Energy transitions are based on the notion that an energy resource, or a group of energy resources, dominates the market for a period or era, until it is challenged and eventually replaced by other(s) resource(s) (Jaeger, 2014). The speed and necessity for a transition is measured by the degree of challenge that the energy resource(s) which will be subsequently replaced present to the society. Historical energy transitions have usually been characterized by a slow gradual pace especially the transition from traditional energy to coal which was triggered by of the industrial revolution and the discovery of the steam engine at the end of the 18th century. The graph below shows energy transitions are completely effective in a period of 100 years.

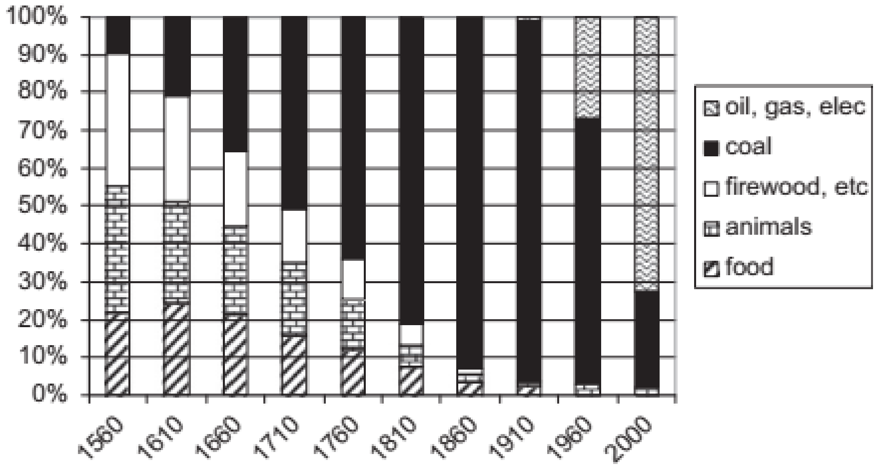


Figure 2-9: From plants to fossil fuels, 1560–2000

Source: (Allen, 2012)

Looking at the transition from plants to coal and from coal to oil, gas and electricity, it will be a realistic guess than the transition from fossil to renewables will be the same order of magnitude of time. However, the transition from fossil to renewables now present constraints which raises urgency to act. (Sgouridis et al., 2015) describes this process as the sower's strategy:

> a key characteristic of SET becomes critical: it requires energy to construct the necessary RE infrastructure and to massively integrate these mostly variable sources in the energy system. At present, the world's energy remains primarily from fossil sources and, as a consequence, we need energy from fossil fuels to move away from fossil fuels. We may see this requirement as analogous to "the sower's strategy", the long-established farming practice to save a fraction of the current year's harvest as seeds for the next. Fossil fuels produce no "seed" of their own but we can "sow" what these fuels provide: energy and minerals to create the capital needed for the transition.
>
> (Sgouridis et al., 2015)

The transition from fossil fuels to renewable energy systems requires a deep understanding of the fossil resource depletion, renewable energy resources and capital and the energy economy as three key sub systems that make up the energy ecosystem.

(Csala, 2016) created a representative model of the fossil and renewable energy systems to capture the transition dynamics as a function of energy demand. As fossil resources become less available, the energy investment and subsequent financial investments increase with time and therefore their demand falls with time thereby favouring a transition to renewable energy systems.

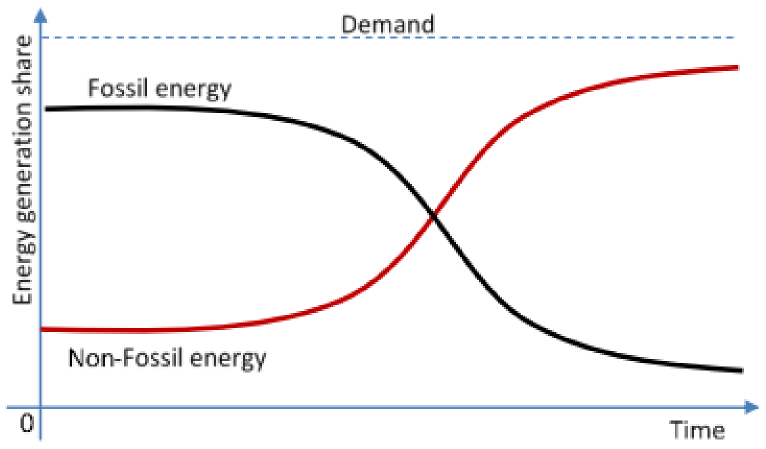


Figure 2-10: Fossil and non-fossil energy demand pathway

According to (Sareen & Haarstad, 2018), sustainable energy transitions must include the socio-technical aspects as well as important implications for social justice. In addressing the all sustainable transitions, the quality of life after these transitions must have occurred must be clearly addressed. It would not be termed sustainable if the quality of life after the transition becomes worse or more difficult than before the transition. (Sareen & Haarstad, 2018) further argue that comprehensive transition approach requires analyses to account for the co-evolution of institutional change, material change and relational change, with a cross-cutting concern for multiple spatialities and normative implications.

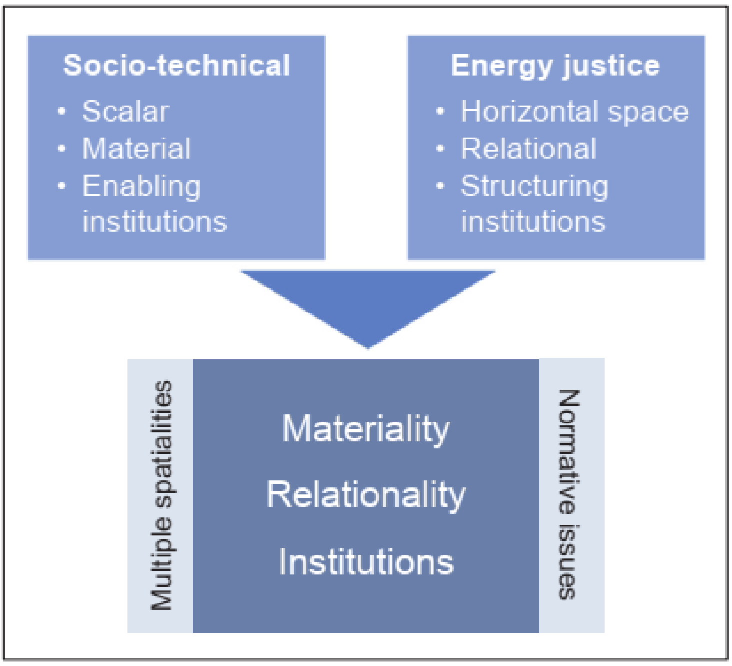


Figure 2-11:Socio-technical and energy justice aspects for sustainable

Source: (Sareen & Haarstad, 2018)

It becomes evident that the criteria involved in assessing sustainable energy transitions are numerous and complex.(Child, Koskinen, Linnanen, & Breyer, 2018) further explained that operationalising sustainability criteria into energy scenario creation, therefore, involves judging how and where the criteria impacts the process. For example, using a resource efficiently not only implies examining efficiency of end-use technologies, but also includes potential improvements downstream and upstream in the supply chain.

Sustainable energy transition is a complex phenomenon which involves technological innovation, efficient policies, energy justice and sustainable use of resources just to name a few.

It is of utmost importance to mention that, although a sustainable energy transition and a transition to a low carbon economy are often used interchangeably, however, a sustainable energy transition combines a transition to a low carbon economy as well as a transition to a stable and reliable supply of energy. Transitions to low carbon economy focuses principally on the total CO_2 emissions which should be kept below a certain level (IEA, 2015). However, a sustainable energy transition, though it includes a low or zero carbon economy, it also addresses fossil resource depletion. Therefore, renewable energy systems are the dominant attributes of a sustainable energy transition while a transition to a low carbon economy involves a combination of many attributes amongst which are: energy end-use efficiency, supply efficiency, renewable investment, carbon capture and storage and to a greater extend nuclear power. The new policies of the IEA are instituted to reduce the total global emissions in the quest to ensure and assure a low carbon economy and consist of the different elements as showed below.

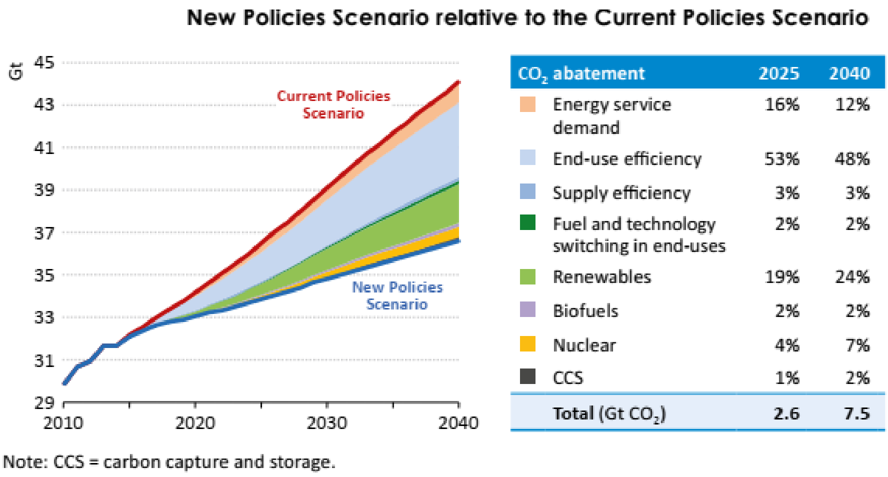


Figure 2-12: Different Interventions for a Low Carbon Economy Transition

Source: (IEA, 2015)

This study will only be limited to resource availability in time and the study will not address the externalities caused by fossil resources, the emphasis of the study will focus on how profitable it will be to operate and run future renewable and fossil energy systems. The most reliable metric to evaluate the profitability of energy systems in time is to evaluate their energy return on energy invested which is discussed in the next paragraph.

2.3 Energy Return on Energy Invested (EROEI)

Energy return on investment (EROEI, or sometimes energy return on energy invested, EROEI) is the ratio of energy returned from energy exploration and exploitation activities compared to the energy invested in those energy-gathering processes(Lambert, Hall, & Balogh, 2013). According to (Csala, 2016) and (Murphy, Hall, Dale, & Cleveland, 2011), the EROEI has four key variables

- $E_g = \int_{t_0}^{t} \dot{E}_g \, dt$, the energy generated by the project
- $E_c = -\int_{t_0}^{t} \dot{E}_c \, dt$, the energy expended to construct the project
- $E_{op} = -\int_{t_0}^{t} \dot{E}_{op} \, dt$, the energy expended to operate the project
- $E_d = -\int_{t_0}^{t} \dot{E}_d \, dt$, the energy expended to decommision the project

The EROEI is define as: $$EROI = \frac{E_g}{E_c + E_{op} + E_d}$$ Equation 2-1

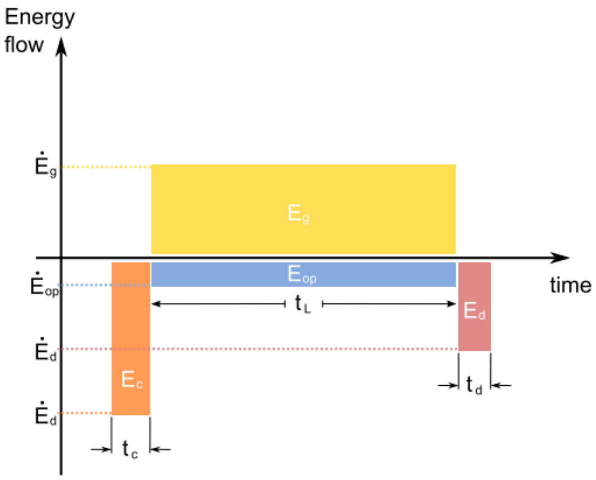


Figure 2-13: Energy Inputs and Outputs for an Energy Production Project

Source:(Murphy et al., 2011)

(Csala, 2016) created a modified diagram of Figure 16 where he compared the different energy values for fossil and renewables. Renewable energy production is characterized by their huge capital investments which translates as a high energy expended to construct the project but have very low operational cost unlike fossil projects which have very high operational cost and relatively low capital investments compared to renewable projects of the same capacity.

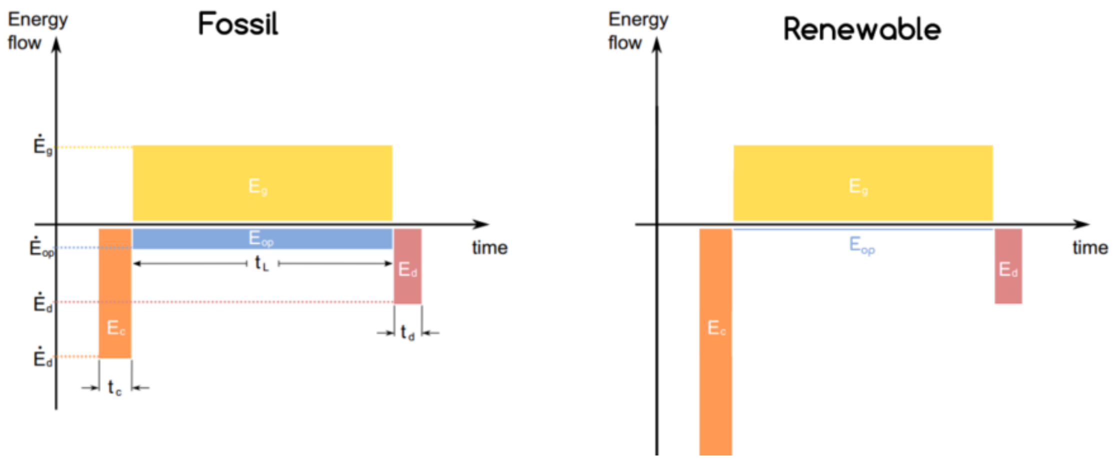


Figure 2-14: Comparing Energy Inputs-Outputs for fossil and renewables

Source:(Csala, 2016)

(Hall, Balogh, & Murphy, 2009) in the article "What is the Minimum EROEI that a Sustainable Society Must Have?" defined three classes of EROEI.

- EROEI of societal denoted $EROI_{Soc}$
- EROEI of point of Use denoted $EROI_{Pou}$

- Extended EROEI denoted $EROI_{Ext}$

According to Hall et al, these three different classes of evaluating EROEI though still present a lot of complexities on the methodology, they succeeded to develop equations to evaluate each class of EROEI and this information is useful in evaluating the minimum EROEI a society can have.

Table 2-3: Different Significance of EROEI

$EROI_{Soc}$	$EROI_{Pou}$	$EROI_{Ext}$
the overall EROEI we might eventually derive for all of a nation's or society's fuels collectively by summing all gains from fuels and all costs from obtaining them	It is defined as the ratio of the energy returned to the society to the energy required to obtain the available energy	"extended EROEI", includes the energy required not only to get but also to use the energy.
$\frac{Summation\ of\ the\ energy\ content\ of\ all\ fuels\ delivered}{Summation\ of\ all\ the\ energy\ costs\ to\ get\ those\ fuels}$	$\frac{Energy\ returned\ to\ society\ Energy}{Energy\ required\ to\ get\ and\ deliver\ that\ energy}$	$\frac{Energy\ returned\ to\ society}{Energy\ required\ to\ get,\ deliver,\ and\ use\ that\ energy}$

A key attribute of obtaining the accurate evaluations of the EROEI is the system boundaries which are crucial for the evaluation process. (Raugei et al., 2017) advised against using extended boundaries which stretches the value of this EROEI beyond its initial intended purpose, and the vast uncertainties involved in doing so make it a risky enterprise that might easily lead to wrong policy choices. According to (Murphy et al., 2011), choosing the appropriate boundaries for an EROEI analysis depends largely on two factors: (1) what level of energy inputs are going to be considered in the analysis and (2) the methods chosen to aggregate energy units.

EROEI is use to represent how much proportion of a fuel's energy is available for use by a society. An EROEI of 1:1 means all the energy available that could have been available to the society is used for process of harnessing and making the energy available. Therefore, the energy source cannot deliver useful energy to the society. Similarly, and EROEI of 100:1 means it the energy resource (fuel) will return 100 times the energy that has been invested in the processing of harnessing it; that means if 20 TJ of energy equivalent has been invested in the process of obtaining the energy, the energy output from all processes of harnessing the energy will be 2000 TJ which will be energy useful to the society. From this analysis, it becomes clear that the EROEI determines the amount of useful energy available to a society and consequently the quality of life. High EROEI fuels allow a greater proportion of that fuel′s energy to be delivered to society (Lambert, Hall, Balogh, Gupta, & Arnold, 2014) and are therefore favorable and desired while low EROEI will deliver lesser energy to the society.

The conventional literature of EROEI focused solely on the static values of EROEI of the fuels, this approach assumes that the EROEI of a given energy resource (fuel) is a constant value and doesn’t change with time.

(Lambert et al., 2014) established a graphical representation of the EROEI and the net energy return for different energy resources. However, the values of the EROEI established are static and not subject to any dynamic change.

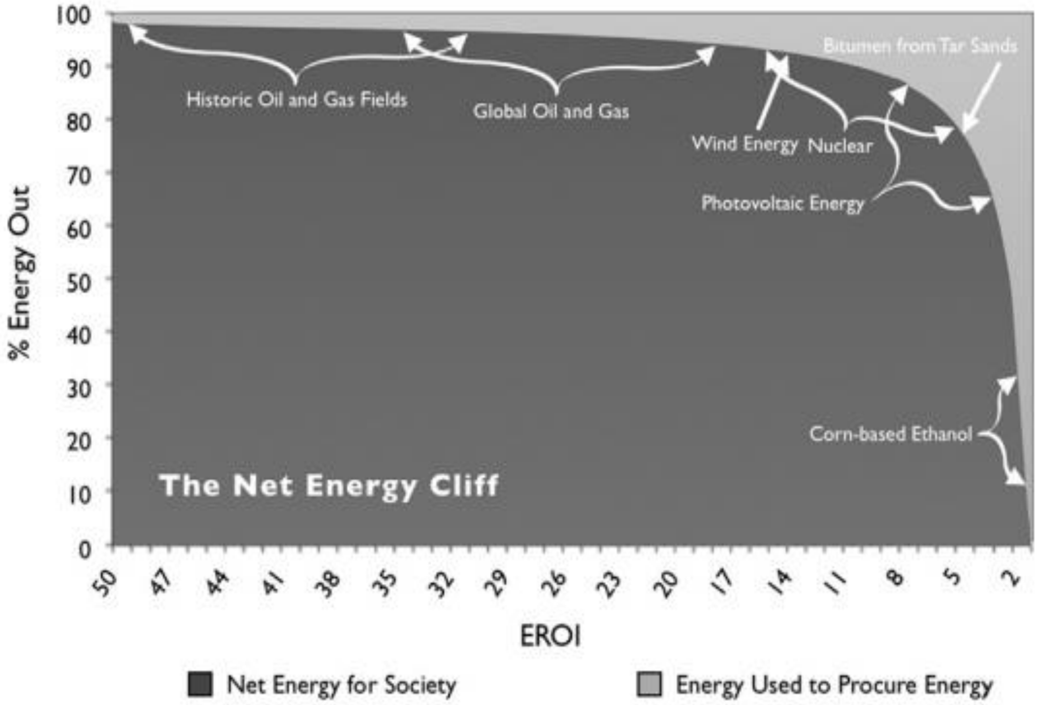


Figure 2-15: EROEI of Different Energy Sources and their Net Energy

Source:(Lambert et al., 2014)

A nouvelle approach of dynamic function of EROEI has evolved over the years. The dynamic function of EROEI has been used by (Michael Dale, Krumdieck, & Bodger, 2011), (Michael Dale, 2010) and (Csala, 2016).

The dynamic EROEI is a timeseries evaluation of the EROEI and intelligent assumes that the EROEI of any energy resource will change positively or negatively with time and depends on two key factors:

- **Physical Component**

- As fossil resources are exhaustible, and as more of the resource is exploited, the quantity remaining termed the ultimately recoverable resource (URR) decreases and therefore requires more energy to exploit the remaining resource. As the energy required to exploit the remaining resource continuously increase as there ultimately recoverable resource decreases, the EROEI therefore cannot stay constant. It is therefore a dynamic function which changes with time.
- Similarly, for renewables, the effect of physical component is not too great. Since renewable energy resources occur freely in nature and are inexhaustible, the effect of physical component is interpreted to be the exhaustion of sites with high resource quality and good generation potential.

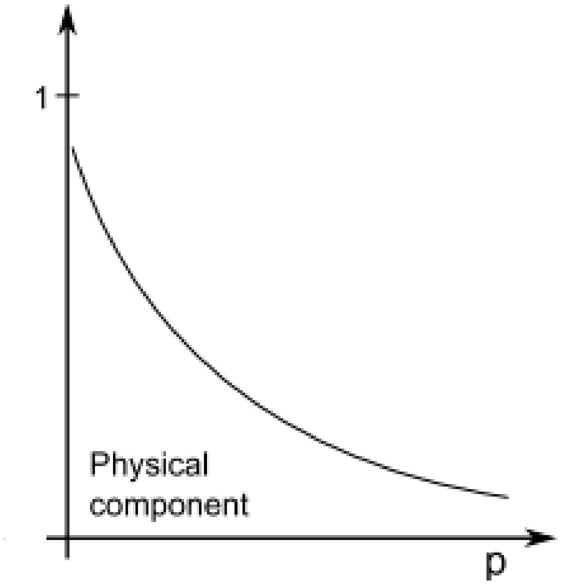


Figure 2-16: Physical Component as a function of production

- **The level of technological progression:**
  - The level of technological progression influences the amount of energy invested in exploiting an energy resource. It is logical that, as a technology matures, i.e., as experience is gained, the processes involved become better equipped to use fewer resources: PV panels become more efficient and less energy intensive to produce; wind turbines become more efficient and increasing size allows exploitation of economies of scale. These factors serve to increase energy returns. (Michael Dale et al., 2011).

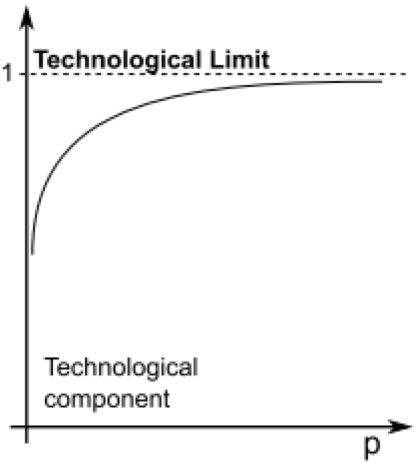


Figure 2-17:Technological Progression of an Energy Technology

Combining the two curves of physical component and technological progression; we obtained the EROEI representative curve as shown below

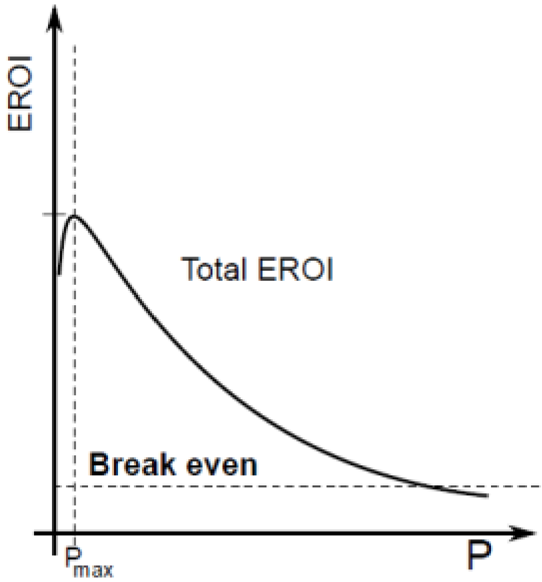


Figure 2-18: EROEI time series

(Csala, 2016) created a comprehensive diagram of how the two interactive components of EROEI change with cumulative production (p)

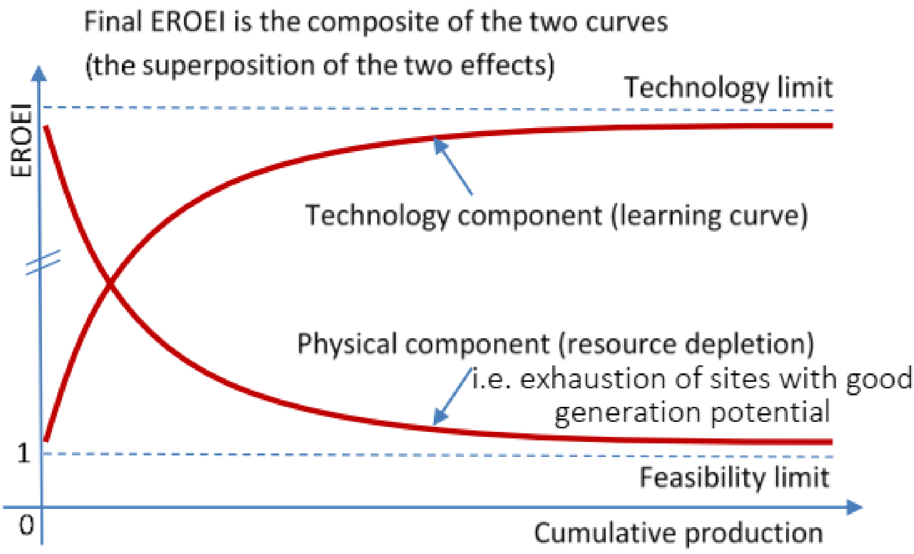


Figure 2-19: Superposition of Technological Progression and Physical Component of Resource

Source: (Csala, 2016)

2.3.1 Mathematical Formulation of Dynamic EROEI

(M. Dale et al., 2012b) established that the EROEI function was a product of the two functions; technological progression and physical component or resource (resource depletion).
Mathematical EROEI is expressed as:

$$\boldsymbol{EROI_k = \varepsilon_k F(p_k)}$$ **Equation 2-2: Dynamic Function of EROEI**

Where the subscript k denotes the energy resource under investigation

F is the function of availability of the energy resource p_k

Similary, the availability of the energy resource p_k can be further defined to include the technological progression and the physical component

$$\boldsymbol{EROI_k = \varepsilon_k F(p_k) = \varepsilon_k\, G(p_k) H(p_k)}$$ **Equation 2-3: Detailed Dynamic EROEI**

Where $\boldsymbol{G(p_k)}$ represents the technological progression and is an asymptotically increasing function (M. Dale et al., 2012b)

$H(p_k)$ is an asymptotically decreasing function, representing declining resource quality.

ε_k is the maximum possible energy return of that resource?

Figure 2-20: Table of Variables Used in Dynamic EROEI

ε_k	$G(p_k)$	$H(p_k)$
is the maximum possible energy return of that resource?	$\mathbf{1-\gamma e^{-\xi p}}$	$\boldsymbol{\phi e^{\psi p}}$
	$\mathbf{0 < \gamma < 1}$ γ represents the initial value of the technology and ξ the rate of technological learning through experience	$\mathbf{0 < \phi < 1}$ $\boldsymbol{\phi}$ represents the initial value of physical component and ψ represents the rate of degradation of resource due to exploitation
Dimensionless	Dimensionless	Dimensionless

p or p_k defined as the availability function according to (M. Dale et al., 2012b) represents how much of the energy is currently being produced normalised with respect to the total available resource for that energy resource. The availability function is then defined separately for renewable and fossil resources as using the same mathematical formula.

$$p_{k_{renewable}} = \frac{\textit{Total Annual production}}{\textit{Technical potential of the Renewable Energy resource}}$$

Equation 2-4: Normalized Production for Renewables

$$p_{k_{fossil}} = \frac{\textit{Cumulative sum of annual production}}{\textit{Ultimately recoverable resources}}$$

Equation 2-5: Cumulative normalized Production for Fossil

Combining the two functions $G(p_k)$ and $H(p_k)$ defines the dynamic function of the energy return of energy investment.

The general practice of modelling energy systems has been solely focused on price and profits and loss statements, this is in fact true as no energy system will operate if the income it generates is less than the investments used to build and operate the energy system. Biophysical economics and modelling of the energy economy this thesis adopts focused solely on the EROEI metric. However, (King & Hall, 2011) showed that EROEI and the price of energy are inherently inversely related such that as EROEI decreases for depleting fossil fuel production, the corresponding energy prices increase dramatically. They further explained that for a firm to make a profit, it has to have some value of positive EROEI because the energy flows associated with its costs are much less than the energy associated with a dollar’s worth of its product. This attribute more importance to biophysical economics as it involves the laws of thermodynamics and also can be used to relate the EROEI to the financial return on investment. The question which arises is what is the link between the EROEI and the financial return on investments otherwise referred to as the monetary return on investment (MROI)? To answer this question, (King & Hall, 2011) established the following formula below.

$$EROI = \frac{\sum_{i=1}^{M} \mathrm{m}_i e_i}{\sum_{i=1}^{M} \mathrm{m}_i p_i} \cdot \frac{MROI}{e_{investment}}$$

Equation 2-6: Relationship Between EROEI and MROI

$\boldsymbol{m_i}$ *represents the unit production of the* i^{th} energy product

$\boldsymbol{e_i}$ *represents the energy intensity expressed in units of energy per physical quantity*

$\boldsymbol{p_i}$ *represents the price of the* i^{th} energy product

$\boldsymbol{e_{investment}}$ *represents the intensity of the investment*

M is the number of output energy products

The monetary return on investment which determines the energy price as well as other financial components of the energy system is defined from first principles as

$$MROI = \frac{\$_{out}}{\$_{investment}} = \frac{\sum_{i=1}^{M} \mathrm{m}_i p_i}{\$_{investment}}$$

Equation 2-7: Relationship between MROI and Investments

$\$_{investment}$ is the monetary value of the investments in the energy system.

2.4 Net Energy Analysis (NEA)

The concept of Energy return ratios (EROEI) can be used to determine the net energy that can be available to a society. Net energy analysis (NEA) is a broad class of methods used to determine the effectiveness of energy capture and conversion systems.(Brandt & Dale, 2011). Net Energy Analysis (NEA) is a structured, comprehensive method of quantifying the extent to which a given energy source is able to provide a net energy gain (i.e., an energy surplus) to the end user, after accounting for all the energy losses occurring along the chain of processes that are required to exploit it (i.e., for its extraction, processing and transformation into a usable energy carrier, and delivery to the end user), as well as for all the additional energy 'investments' that are required in order to carry out the same chain of processes. (Raugei, Frischknecht, Olson, Sinha, & Heath, 2016). The goals of NEA were stated by (Raugei et al., 2016) as follows:

- descriptive assessment of the viability of a particular technology (e.g., solar satellite);
- comparative assessment of alternative energy technologies;
- calculation of the (minimum) EROEI to support an industrial society, or alternatively assessing the feasibility of some technology to (singlehandedly) support an industrial society.

$$Net\ Energy = Energy\ Output - Energy\ Input$$

Similarly, the NEA can be expressed in terms of the EROEI as follows:

$$EROI = \frac{E_{output}}{E_{input}}$$

$$Net\ Energy = E_{output} - E_{input}$$

$$but\ the\ E_{input} = \frac{E_{output}}{EROI}$$

$$\Rightarrow \boldsymbol{Net\ Energy = E_{output}(1 - \frac{1}{EROEI})}$$

Equation 2-8: Relationship between Net Energy and EROEI

From the formula above, if the EROEI=1, the Net Energy =0, signifying no useful energy is delivered to the society. From this equation, we can ascertain that there exist a minimum EROEI for which an energy resource should have for it to deliver sufficiently large Net Energy useful to the society.
To quantify the relationship between the net energy and the EROEI, we define a new function, β representing the Net Energy per unit output energy delivered to the society

$$\beta = (\boldsymbol{1 - \frac{1}{EROEI}})$$

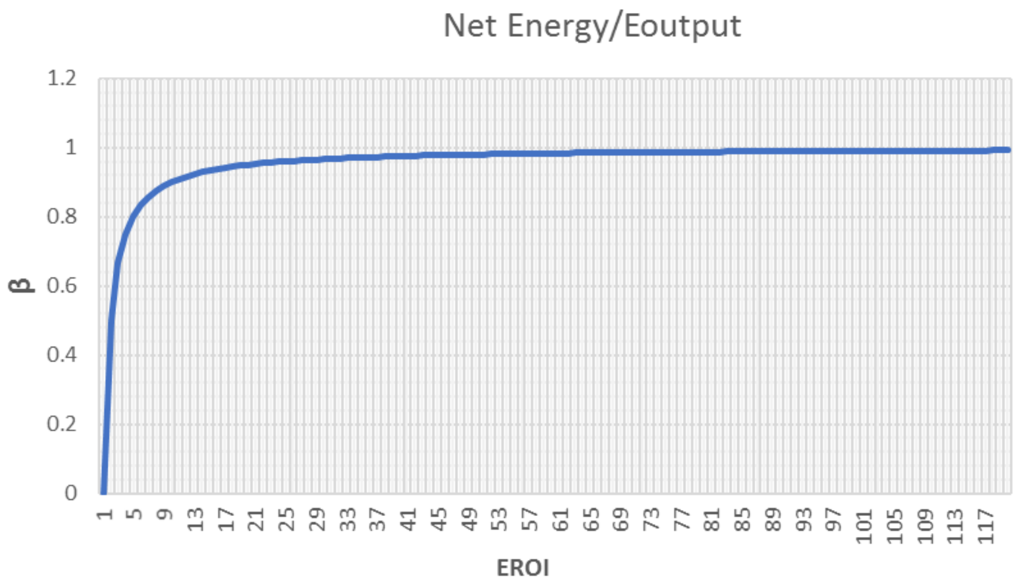


Figure 2-21: Relationship between Net Energy and EROEI

It is clearly evident that higher values of EROEI are better and that as EROEI increases (EROEI >=50), the Net Energy per unit output power delivered to the society equals one (β=1). The significance of these are summarized below:

- very low values of EROEI mean the energy sources are energy sinks taking up more than they deliver to the society.
- Very high values of EROEI are ideal as the energy inputs into harnessing the energy resources are negligible compared to the net energy delivered to the society.

This study therefore focuses on these two metrics: the EROEI and the Net Energy for Ghana and for each resource quantify the dynamic function of EROEI for a given period of time. For each yearly value of EROEI obtained per resource under investigation, the associated Net Energy delivered from that resource will be calculated. Since the quantity and the quality of energy determines the quality of life and economic growth, these values will help shape the dynamics and policies of implementing a sustainable transition to a stable energy system

DESCRIPTION OF CASE STUDY

3.1 Location (Ghana)

Ghana is a West African country bounded by Burkina Faso on the North, on the East by Togo and the West by Cote d' Ivoire and on the south of the Atlantic Ocean. Ghana which was formerly Gold Coast was a British colony(Oteng-bosomprah, 2016). The country profile is summarized in Figure 3-1 below:

Figure 3-1:Ghana Demographic Information

Population	28833629
Population growth rate	2.19%
GDP per capita, PPP (current international $)	4641.32
Electricity Access rate	79.3%
Public private partnerships investment in energy (current US$)	752000000

Data Source:("World Bank Group" 2018)

Figure 3-2:Administrative Map of Ghana

Source: http://ontheworldmap.com

3.2 Energy Resources

The energy resources listed in Table 3-1 are the available energy resources in Ghana.

According to the EIA (Energy Information Agency), the crude oil reserves for Ghana is estimated at 1.06 Billion Barrels of oil while the Natural gas reserves is estimated at 0.80 trillion cubic feet of gas. (opendatafor Africa).

The oil and natural gas reserves and production for Ghana are summarized below.

Table 3-1:Fossil fuel production

Producing Field	Estimated Recoverable Reserve	Oil Produced (2016)
Jubilee Production	618million barrels of oil	26981.641 mmbls
	505 billion cubic feet of gas	38421MMscf
Ten Development	240million barrels of oil	5.32mmbls
	3.96 billion cufic feet of gas	6532MMScf
Sankofa Gye Nyame	204 million barrels of oil and condensate	
	1071billion cubic feet of gas	

Source: (Rhoda & Ardua, 2017)

According to the statistics present by Rhoda & Ardua and based on the 2016 fossil production, we can estimate the theoretical timeframe for which these fossil resources will be completely depleted assuming a 2016 Business as usual scenario.

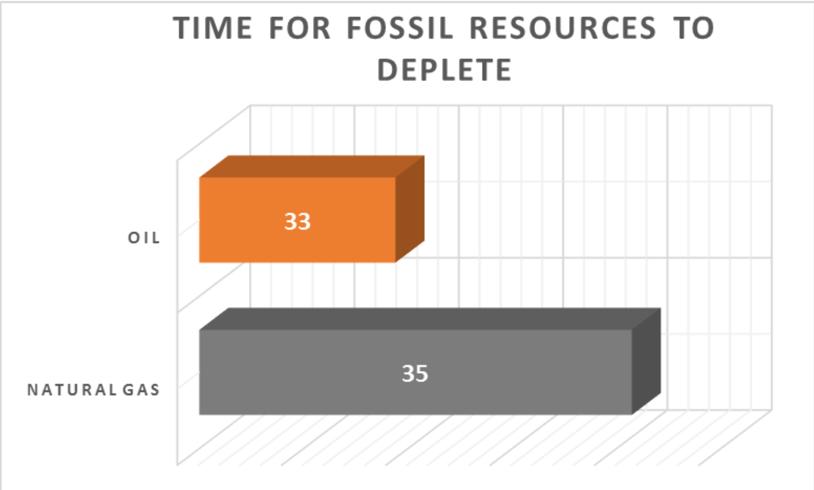


Figure 3-3: Time Estimation for Fossil reserves to deplete

Data source: (Rhoda & Ardua, 2017)

It is based on this estimate of fossil depletion estimated at 33 years for oil and 35 years for Natural gas that this thesis becomes important and indispensable. Though these numbers are just rough estimates and they don't consider the rate at which new reserves are discovered, as well as assumes a constant rate of fossil exploitation (which is likely going to increase as demand for energy increases with population growth), they provide useful information which indicates that these fossil fuels will soon be exhausted before the end of this century and therefore the need for a sustainable energy resource is advocated.

The renewable energy resources in Ghana are principally wind, hydro, solar and biomass. Biomass is used traditionally as fuel for cooking. The National Renewable Energy Laboratory (NREL) assessed the wind and solar energy in Ghana as part of the Solar and Wind Resource Assessment (SWERA) project for the United Nations Environment program. According to the SWERA reports, there are 413 km^2 of areas with good-to-excellent wind resource potential in Ghana, and these windy areas represent 0.2% of Ghana's total land area of 230,940 km^2. Using a conservative assumption of 5 MW per km^2, this windy area could support more than 2,000 MW of potential installed wind capacity (NREL, 2004). If moderate wind resource potential is considered, the total electric power generation potential from wind increases to 5600MW.

Table 3-2:Wind Resource Potential-Good to Excellent

Wind Resource Quality	**Wind Class**	**Wind power at 50m W/m2**	**Wind speed at 50M m/s**	**Total Area Km2**	**Total Installed Capacity potential MW**
Moderate	3	300-400	6.4-7.0	715	3575
Good	4	400-500	7.0-7.5	268	1340
Excellent	5	500-600	7.5-8.0	82	410
Excellent	6	600-800	8.0-8.5	63	315
Total				413	5064

Source:(NREL, 2004)

The wind class or wind speed determines the resource quality. The resource quality which is translated as the physical component of the EROEI is key in determining a timeseries evolution of the EROEI of a n energy resource. In a logical way, energy projects are usually implemented where the resource quality is high, however the total power generated from high resource quality sites are always lower since these sites as few as shown on the table above. As the high resource quality sites decrease, the projects tend to move towards low resource quality sites requiring more land and more energy investments leading to the effect of a decrease in EROEI as more of the high resource quality sites are exhausted. This is analogous of the fossil depletion process for fossil fuels.

The solar resource potential for Ghana was also assessed through the SWERA project conducted by the Deutsches Zentrum für Luft- und Raumfahrt e.V (DLR) between the years of 2000,2001 and 2002 and the following geographic representation of the global horizontal irradiance was obtained.

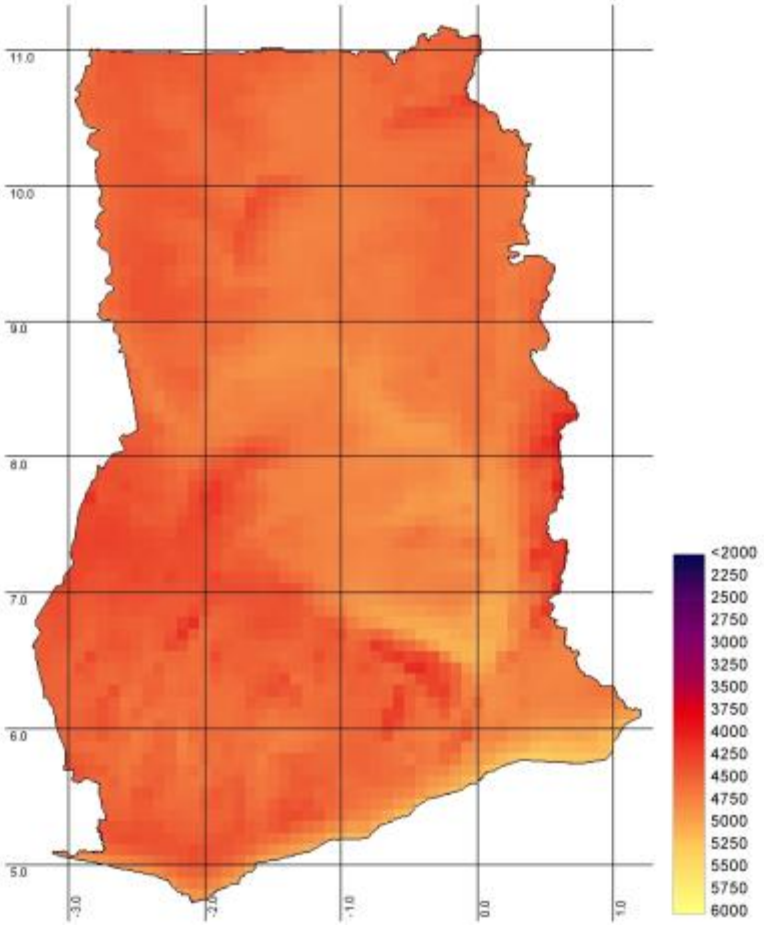


Figure 3-4: Global Horizontal Irradiance for Ghana (2000-2003)

Source: ((Deutsches Zentrum für Luft- und & E.V, 2004)

The SWERA project and the Ghana energy commission estimate the solar resource potential at a daily average between 4 kWh/m2 and 6 kWh/m2.

Data from the Ghana energy commission shows that the integration of renewables in the energy system is still very low. The histogram below shows the total primary energy supply in Ghana in 2016, apart from hydro (which is a scale limited renewable energy resource) which accounts for 5% of the total primary energy supply, solar accounts for less than 1% and the wind energy supply is zero.

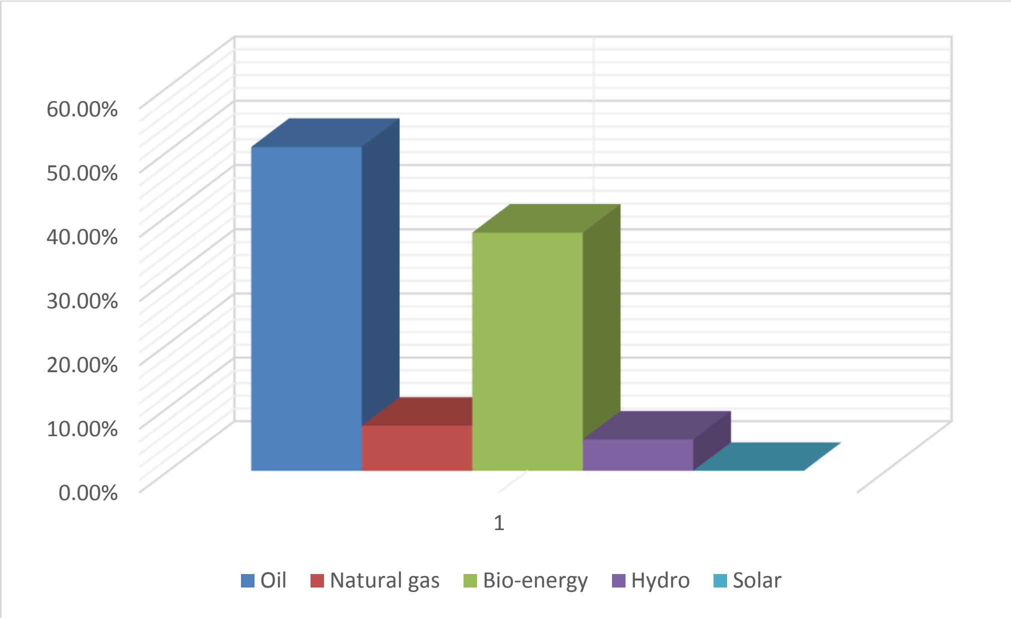


Figure 3-5: Total Primary Energy Supply in Ghana (2016)

Source: (Energy Commission-Ghana, 2016)

The total final energy consumption in Ghana includes principally electricity, petroleum and biomass. Biomass is significantly of high demand as traditional use of biomass for cooking is still in high use. Natural gas is used mainly for electricity generation and petroleum products are used in the transport sector. The difference is the values of total primary energy supply and total final energy consumption as shown on the trends below shows that a huge percentage of the energy is lost between generation sources and demand sites or in the process of use (inefficient systems). Though the available data couldn't permit this research to differentiate this loss according to the different supply resources, however, a quantification of this loss actually shows the level of action and investments needed to increase process efficiency of thermal plants and reduce loss due to electricity transport.

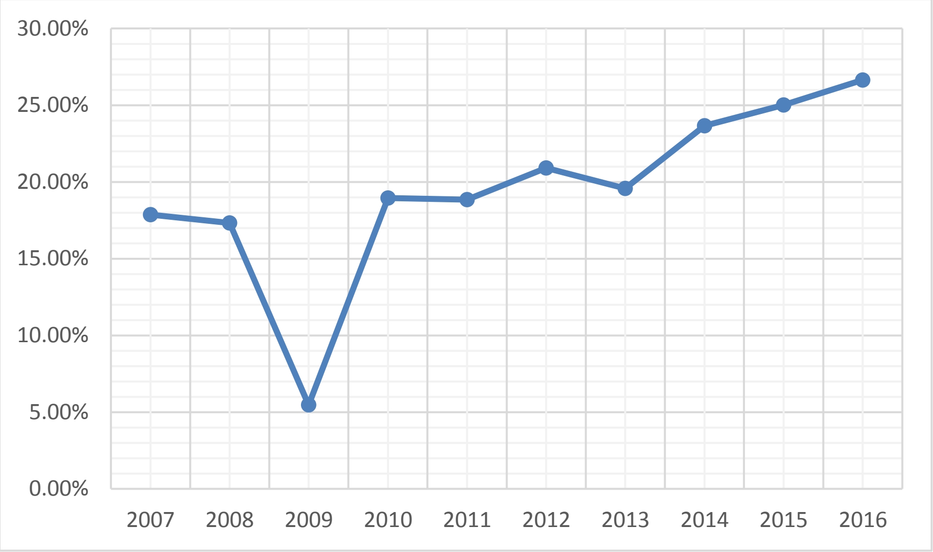


Figure 3-6: % of TPES loss

Data source: (Energy CommissionGhana, 2016)

The sectorial energy consumption for Ghana shows that the residential and the transport have the highest shares of the consumption which correlates with the high biofuel and petroleum products consumption. Industry still has a low percentage of energy consumption but this percentage is envisaged to increase significantly through the years as the country drives its economic growth.

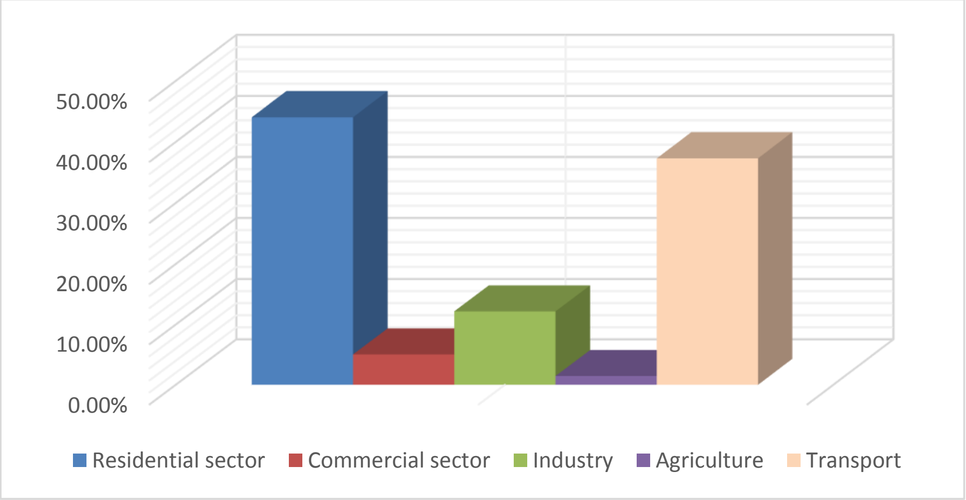


Table 3-3: Sectorial Energy consumption percentage

Data source: Ghana Energy Commission.

3.3 Electricity Generation and Policies

The total installed capacity for electricity generation is 3794.6MW with a total dependable

3525.1MW (Energy Commission-Ghana, 2016). The principal electricity generation sources are hydro and thermal plants and the government of Ghana has envisaged further developments of thermal plants in order to meet with a 100% electricity access rates. Hydro constitutes 41.64% of total electricity production and thermal plants make up 58.46% of the electricity production with solar power production accounting for as low as 0.6% (Energy Commission-Ghana, 2016).

The current electricity access rate in Ghana is estimated at 70% (Hagan, 2015) and is recorded as one of the highest connection rates in sub-Saharan Africa. The electricity policies for Ghana are drafted in the Strategic National Energy Plan (SNEP) and aims at achieving the following (Hagan, 2015)

- Universal access to electricity by 2020 (recently moved forward to 2016) from 70% today (though access in rural areas is only 40%)
- 10% contribution of renewable energy (excluding hydro with capacity of 100 MW or larger) in the electricity generation mix by 2020;
- 5,000 MW of generation capacity by 2020 (recently moved forward to 2016).

There are other electricity policies relating to feed in tariffs and price tariffs but those policies are beyond the scope of this thesis. The thesis will only focus on electricity generation policies and demand.The projected capacity for Ghana according to (Rhoda & Ardua, 2017) is in figure 3-7

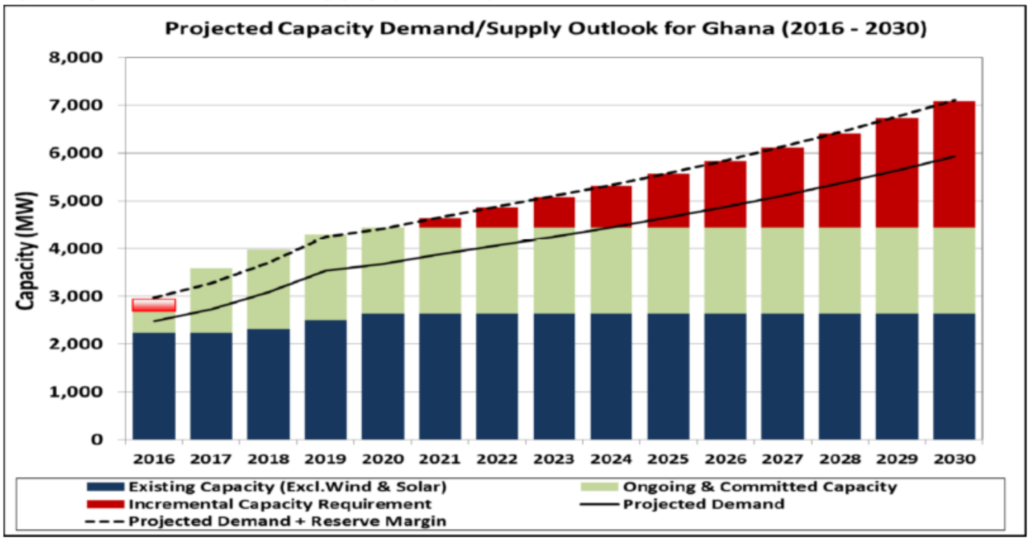


Figure 3-7: Projected Capacity Increment for Ghana

Source: (Rhoda & Ardua, 2017)

METHODOLOGY

In this chapter, we will identify the methodology used to evaluate the EROEI. Evaluating EROEI entails a correct choice of many parameters and factors that affect it. The choice of the systems boundary and the different resources under assessment and the time frame for which the dynamic function of EROEI is to be evaluated. Generally, according to past literature;(Murphy et al., 2011),(M. Dale, Krumdieck, & Bodger, 2012a),(Michael Dale, 2010),(Raugei et al., 2017), the following steps will be adopted in this chapter to evaluate the dynamic function of the EROEI.

- Stating the objectives of the study:
  - Evaluating the EROEI for the different resources is to allow a comparative assessment of the performance of different energy resources with time.
- Identification of system boundaries:
  - The geographic location chosen for this study is Ghana and the energy resource under consideration are solar, wind, natural gas and petroleum oil. It is imperative to mention that though hydro is renewable energy resource, its exploitation in Ghana has reached maximum and therefore no further hydro power plants can be developed to carter for the growing demands. So, hydro will be excluded in the EROEI evaluations as it near maximum exploitation and presents no future prospects regarding new hydro plant development. Our renewables in this case will be mainly solar and wind which are scale limited resources.
- Identification of variables needed for evaluating the EROEI within the system boundaries developed.
- Creation of a causal loop diagram and stock and flow diagrams.
- Evaluation of EROEI and sensitivity analysis.

The variables in this project will be divided into three main groups: the renewable energy system variables, the fossil energy system variables and the economy variables. The variables will be used to define the causal loops of each system and a stock and flow diagram will be created in Vensim with associated mathematical equations and programming to evaluate the different variables of the system.

In System dynamic modelling, the variables are usually grouped into exogeneous or endogenous variables. Exogeneous variables are variables that don't not have dynamic interactions with the overall system while endogenous variables are those whose behaviour are dynamically dependent on the other variables included in the model. In our model, we will consider the following assumptions:

- Energy demand is exogeneous and therefore people will continue to need energy even when the resources required to provide the needed energy are completely used or depleted.

- If an energy resource is completely used or depleted, the supply of energy will be provided by the remaining alternative energy resources until when one or all of them are completely exhausted.

In the model we will develop, apart from energy demand which will remain exogeneous throughout the model, the rest of the variables will be endogeneous.

Table 4-1:Renewable Energy Sub system

Variable	Description of physical implications	Model Units
technical potential	Amount of energy that can be exploited from renewable energy sources	GWh/year
technology progression	Improvements in the efficiencies of different RE technologies	Dimensionless constant]0, 1]
Renewable demand ratio	Measures the fraction of the total primary energy supply that is clean energy (excluding traditional biomass)	Dimensionless
Resource quality	This attribute measures how much the resource quality of a renewable energy decreases as many good sites are exploited	Dimensionless
EROEI	Ratio of Total RE Output to the Total RE Input	Dimensionless
Annual production or RE power output	Power produced from RE sources	GWh
Net Energy	Difference in Output Energy and the total Input Energy	GWh
Required RE capital	Amount of capital needed to develop the renewable energy potential	GWh

Table 4-2:Fossil Fuel System Variables

Variable	Description of physical implications	Units
Fossil demand Ratio	Ratio of total primary energy supplied by fossil fuels	Dimensionless]0,1]

Fossil fuels extraction	Rate of extraction of fossil fuels	GWh/year
URR	Ultimately recoverable resources	GWh
Fossil EROEI	Total Fossil Output Energy to input energy	Dimensionless
Fossil Net Energy	Difference between the total output and the total input	GWh
Fossil Resource Depletion	Measures the rate of degradation of the total fossil reserves	]0,1] dimensionless

Table 4-3:Economy System Variables

Variable	Description of physical implications	Units
Energy Demand	Total Energy Requirements of the society	GWh
Energy Ratio	Amount Allocated by country to develop Energy resources	dimensionless

The variables listed above are the ones effectively used in the model to define the transition, but however, the make our causal loop representation meaningful for policy strategy and documentation, other extended variables (extended boundaries) have been added to make the causal loop representation more understandable, but these variables will not be used in the model, they are used simple for explaining the causal loop relationships. These variables include the total country capital, the renewable and fossil capital as well as capital ratios.

To enable a proper model development, we will use parameters which are basically dimensionless constants to enable logical assessment and development of our model.

Table 4-4: Parameter Description

Parameter	Description	Fossil or Renewable
Learning factor	The learning rate which affects the technological progression	Both
Rate of resource degradation	Measures the rate at which a resource depletes and affects resource depletion	Applicable for both but used for fossil
Effect of EROEI on fossil demand	Numerical attribute of influence on EROEI on fossil demand	fossil
Effect of time on fossil demand	Quantifies how by how much percentage fossil demand will increase	Fossil system

4.1 Causal loop diagrams

The first part of methodology consists of developing the different loops involve in affecting the different system variables listed above.

Fossil sub system causal loop

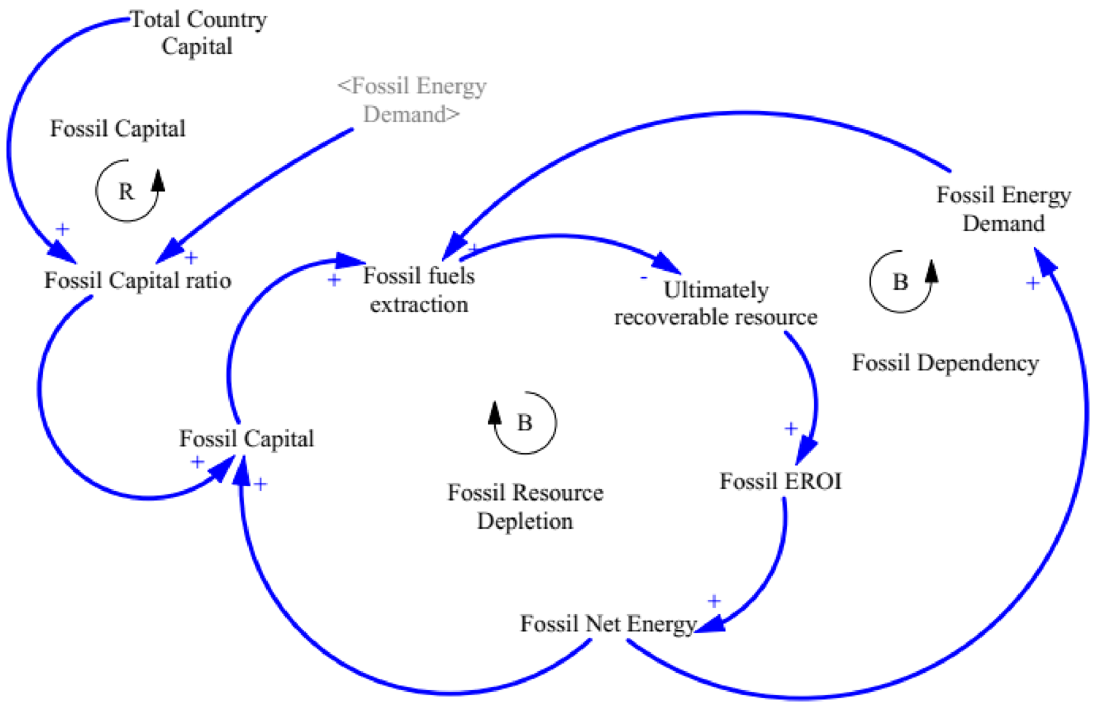


Figure 4-1:Fossil Energy Subsystem

Source: Own work

The fossil resource depletion loop is influenced by fossil capital available for exploitation of the resources, as this capital is increased, the rate of extraction of fossil fuels increases which in turn reduces the ultimately recoverable resources (URR). The URR has positive links with the EROEI indicating their change is in the same sense (i.e, a reduction in URR directly leads to a reduction in EROEI because of the difficulty in extraction and vice versa). The fossil resource depletion loop is a balancing loop as it goes to reduce the URR. Similarly, the fossil energy demand has positive links with the fossil extraction rate and the fossil capital ratio. The fossil net energy which is the useful energy available to the society goes to meet the fossil energy demand which in turn affects the capital ratio allocated for the fossil extraction process. The fossil dependence is a balancing loop as well as the amount of URR reduces with time while the fossil capital loop is a reinforcing loop as the amount of energy capital allocated for the extraction process continues to increase as the URR decreases.

RE Energy sub system Causal loop

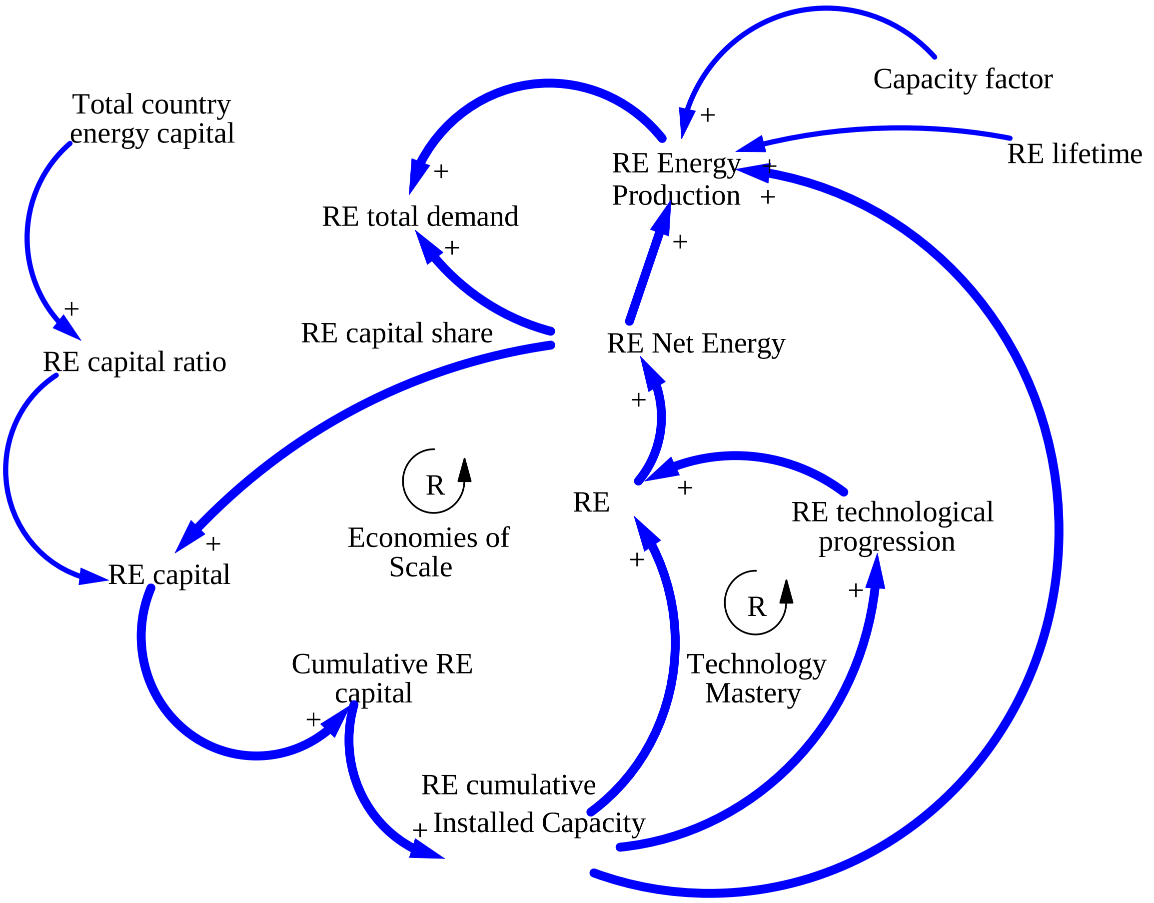


Figure 4-2: Renewable Energy Subsystem

The RE subsystem is characterized by three main attributes which constitute the three main feedback structures in the diagram

- RE capital share
- Economies of Scale
- Technology mastery

As the demand for RE increases due to a fall in demand for fossil (as a result of increasingly lower values of EROEI and Net energy), the RE capital ratio is increased leading to more capital invested in RE energy projects and consequently more installed capacity leading to better mastery of the technology and higher values of EROEI and net renewable energy. As the net energy from renewable increases, the demand for Energy increases.

A more comprehensive diagram joins the two systems (Renewable and fossil) to depict how they change simultaneously as shown below.

Combined Causal loop of the two energy subsystems

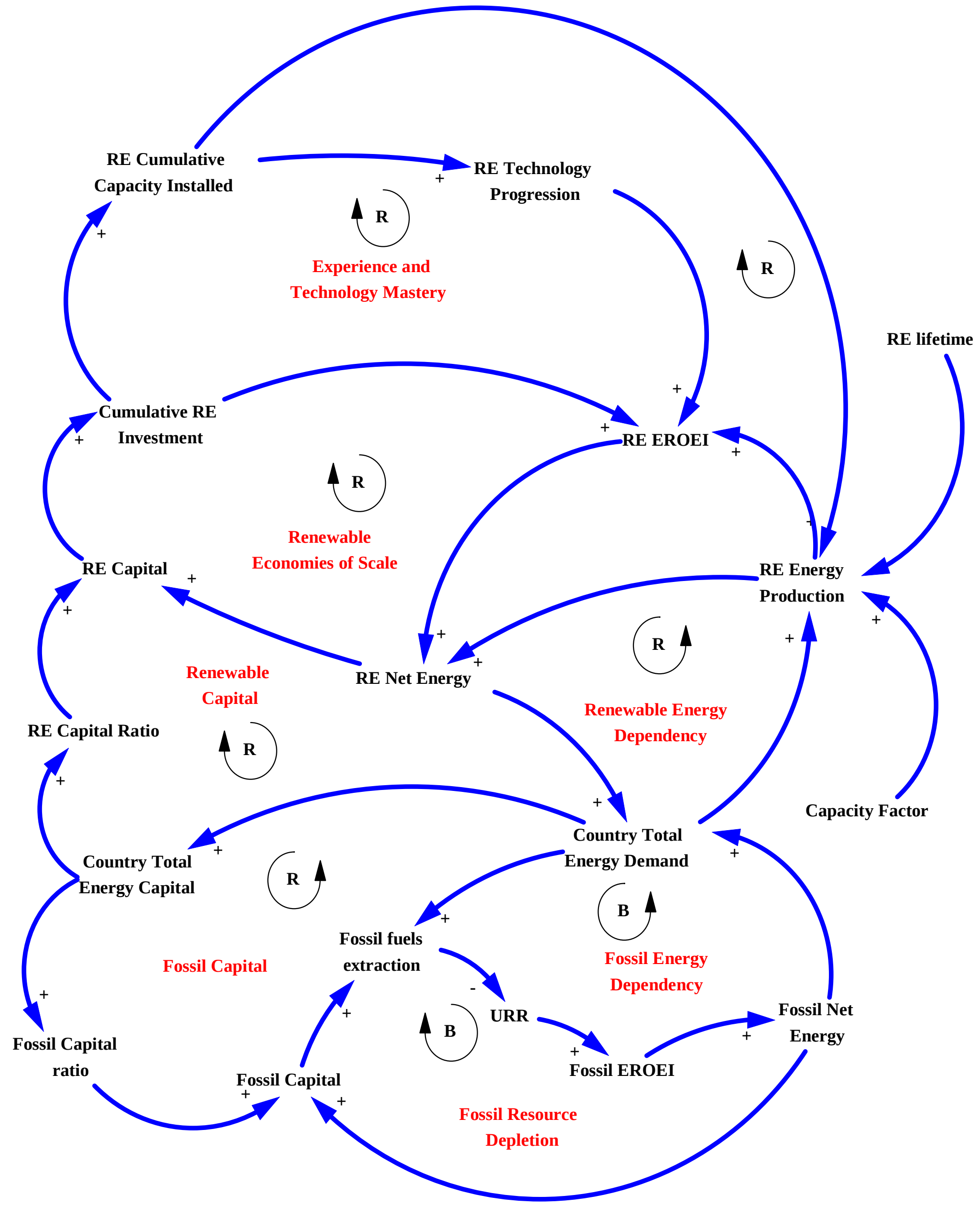


Figure 4-3: Causal loop of the entire Energy system

4.2 Dynamic EROEI

All the different variables listed in the causal loops will be incorporated to form a simplified model of stock and flows for both the fossil and the renewable energy system. The stock and flows have been slightly modified to allow for mathematical formula and calculations.

Fossil system stock and flows

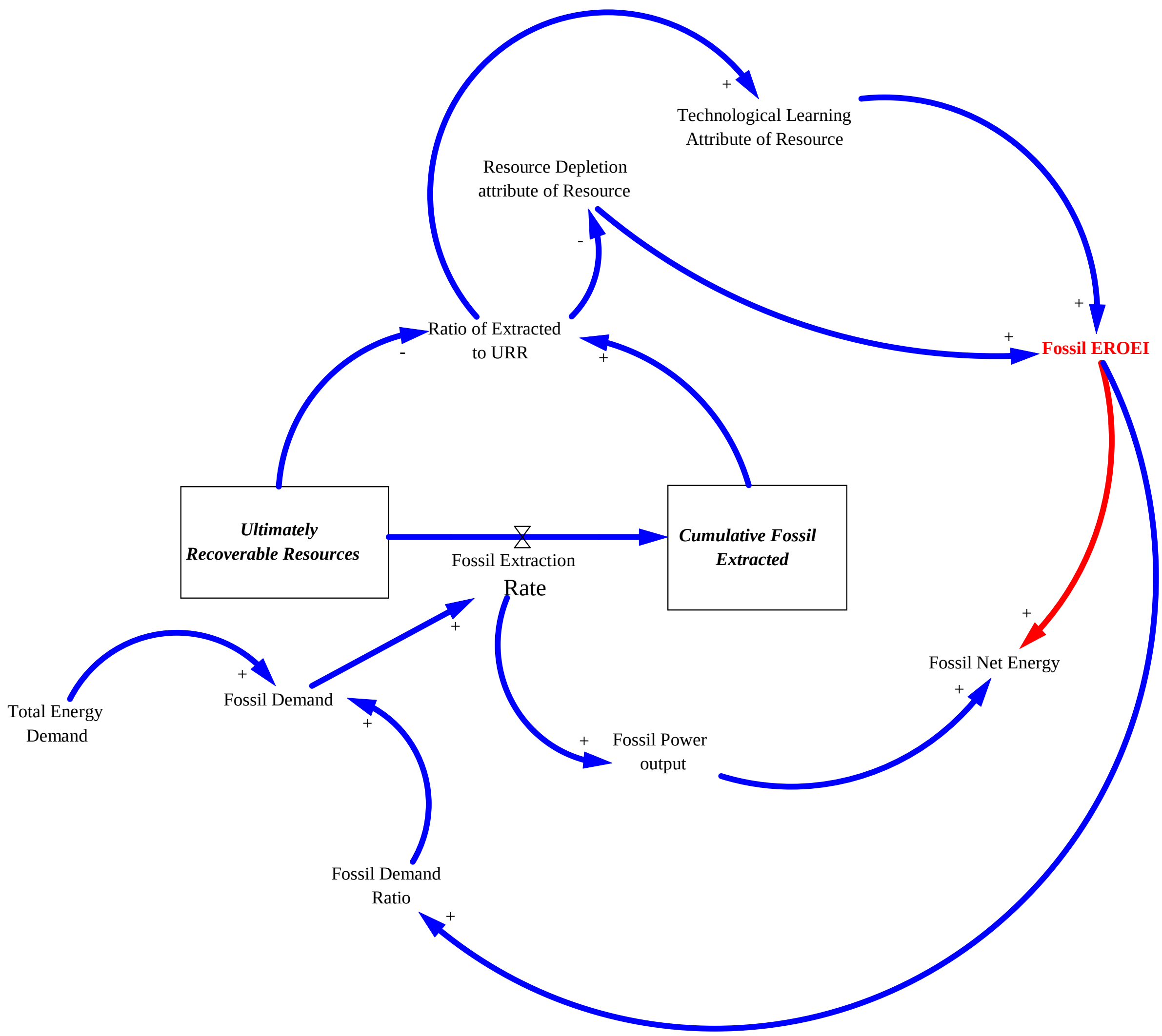


Figure 4-4: Stock and Flows for Fossil sub system

Source: Own work

The fossil sub system stock and flows have to adapted from the causal loop diagram to include components that will be modelled within the scope of this work. The two main stocks in the fossil sub system are the ultimately recoverable resource and the cumulative fossil extracted. Just as in the case of the causal loops for the fossil system explained in 3.3, the stock and flows have a similar explanation. However, a feedback loop has been added linking the EROEI to the fossil demand ratio. In the case of high EROEI, the fossil demand ratio increases and the total fossil demand in turn increases, as the EROEI of fossils decrease, the fossil demand ratio decreases as well as the fossil demand. It is important to state that the fossil demand ratio and the renewable demand ratio sum up to 1.

The causes tree is used to describe how each variable in the loop interrelates with other variables. This is particularly important for qualitative studies (policy formulation) as it permits the policies makers to see at each level the different intervening variables and the how the effect the outcome of other variables.

Vensim provides this special feature to visualize the causes tree and uses tree to enable the modeler visualize clearly and understand hi system.

The following causes tree below have been introduced for the fossil system, however a similar principle applies for the renewable system.

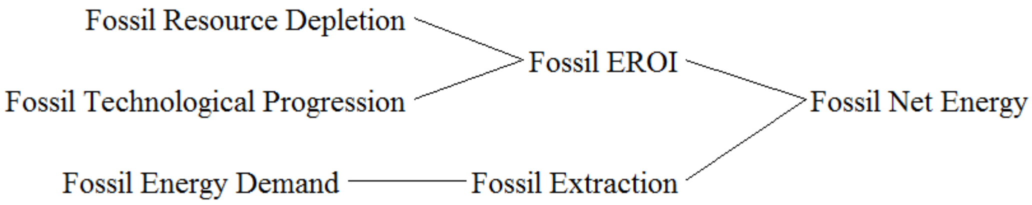


Figure 4-5: Fossil Net Energy Causes Tree

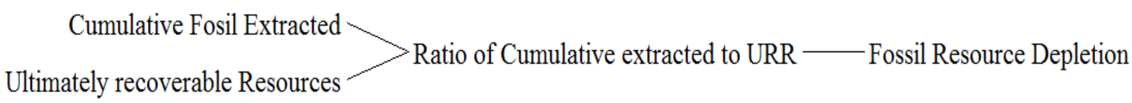


Figure 4-6: Fossil Resource Depletion Causes Tree

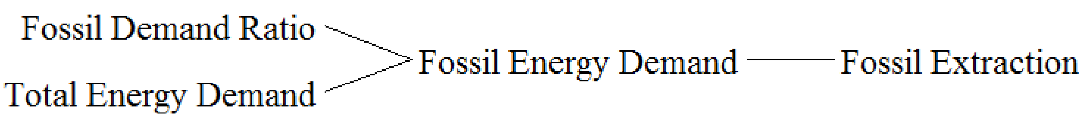


Figure 4-7: Fossil Fuel Extraction Causes Tree

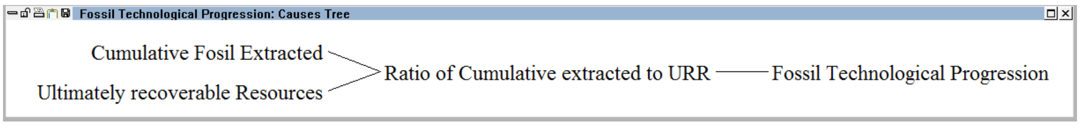


Figure 4-8: Fossil Fuel Technological Progression

Renewable system stock and flows

The renewable system stock and flow diagram looks almost identical to the fossil subsystem since they are based on the same principle, however in the case of renewable, the annual production is only what is important as renewables are inexhaustible (Technical Potential doesn't deplete). The required renewable capital which is defined as the capital requirements in energy units to build the renewable energy system is added in this model

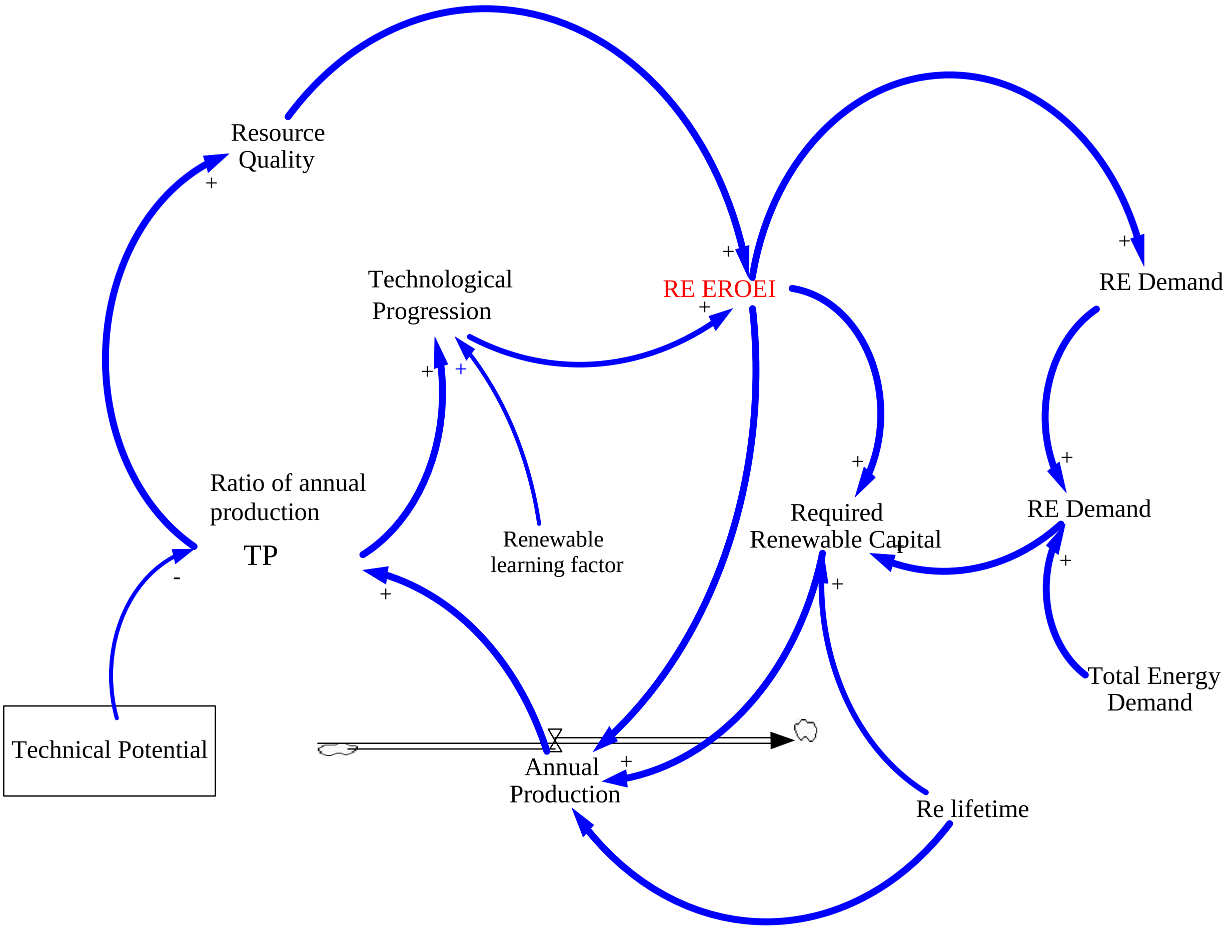


Figure 4-9: Renewable Energy System stock and flow

Source: own work

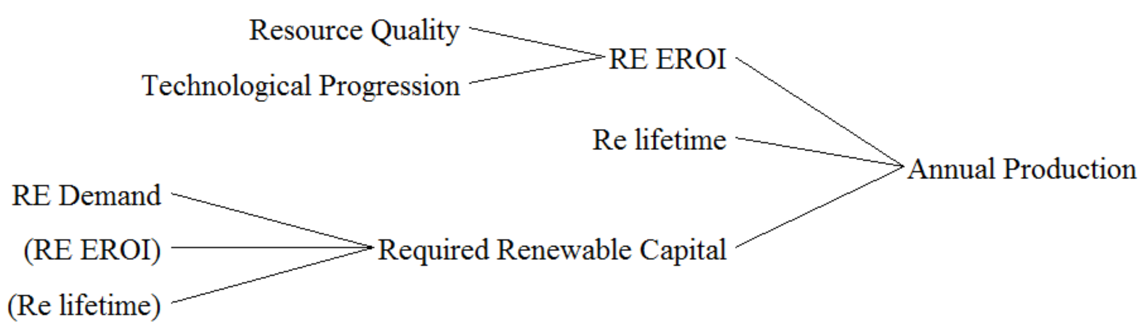


Figure 4-10: Annual Production Causes Tree

4.3 Data Calibration for Model Simulation

4.3.1 Reference Energy Demand Data

One important variable in determining the EROEI is the total primary energy demand. As our study envisages a timeseries evaluation of EROEI up to 2100, we will therefore need to evaluate the total primary energy demand to 2100. Energy demand is assumed to be purely exogeneous and will be forecasted using past data and intelligent assumptions involving economic growth, regression methods and the introduction of new technologies like electric cars and trains.

The study aims at analyzing the returns for a large time interval to completely and correctly capture the dynamics of the movement and the changes in the EROEI. An important aspect of EROEI is the delay- which should allow for sufficient time interval so as to clearly show the changes in the EROEI will occur. In this regard, the thesis envisages an energy demand for the country of Ghana up to the end of the century. Demand is assumed to be purely exogeneous, meaning the energy demand will not depend on the available resources of the country but will depend on other exogeneous factors such as population and economic activities. Although, energy demand most of times can be modelled (forecasted) as an endogeneous variable, however, this kind of modelling of endogeneous energy demand is beyond the scope of this thesis.

According to the IEA, the total primary energy consumption for Ghana trend is shown below

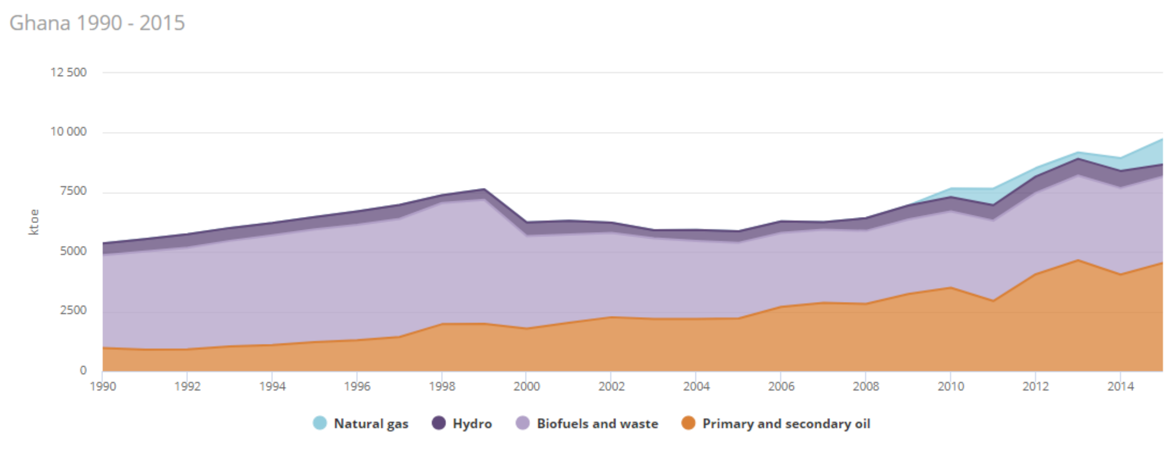


Figure 4-11: Total Primary Energy Supply

Source: IEA

Biofuels and waste constituted a large percentage of the energy consumption but this consumption is principally traditional use of wood for cooking. However, as clearly depicted on the graph, the use of traditional biofuels is significantly decreasing over the years as the country relies on using more petroleum products (petroleum oil and natural gas). To forecast the energy consumption up to 2100, we will make the following assumptions.

- The introduction of renewables (solar and wind) will make up 20% of the total electricity consumption by 2020 (Energy Commission-Ghana, 2006) and 30% by 2030. The values of renewables in the energy mix will keep increasingly significantly until 2100.
- The use of fossil will continue to increase until it reaches a peak year and then starts decreasing as a result of introduction of nouvelle technologies (electric cars) and pressing constraints of climate change.
- Traditional Biomass will decrease significantly and attend a constant value. At this point we will assume the introduction of bio-gas.

The energy demand will be modelled exogeneously using the energy demand per capita Using historical data, a regression curve of the energy demand (TPES) per capita will be created and then a forecast of the energy demand per capita for Ghana up to 2100 will be done.

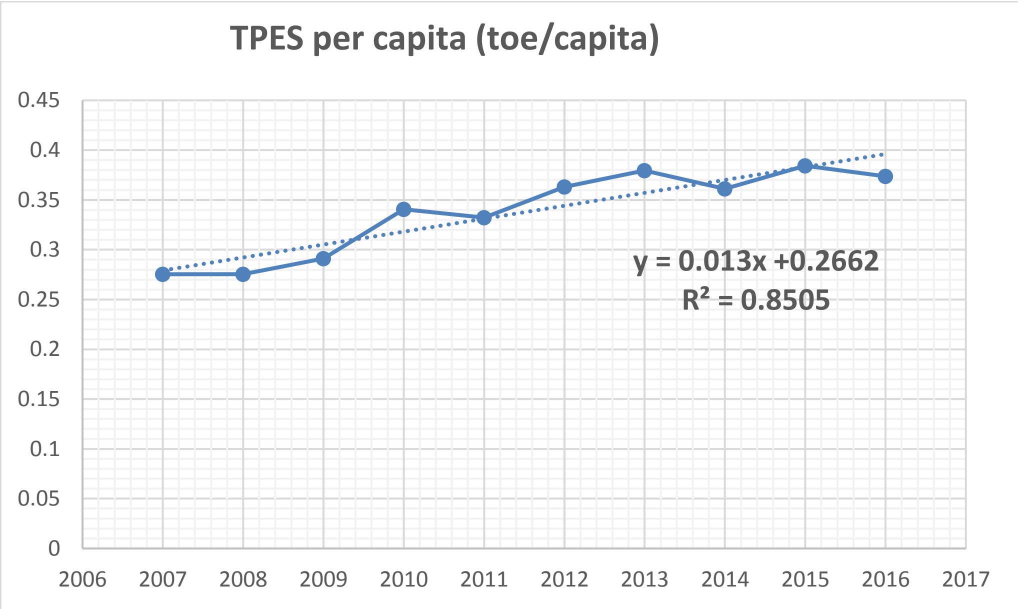


Figure 4-12: Total primary energy supply per capita, historical data regression

Data source: Ghana Energy Commission, World Bank Group 2018

Using the regression equation, we obtain a forecast of the TPES per capita for Ghana to the year 2100 using a business as usual scenario.

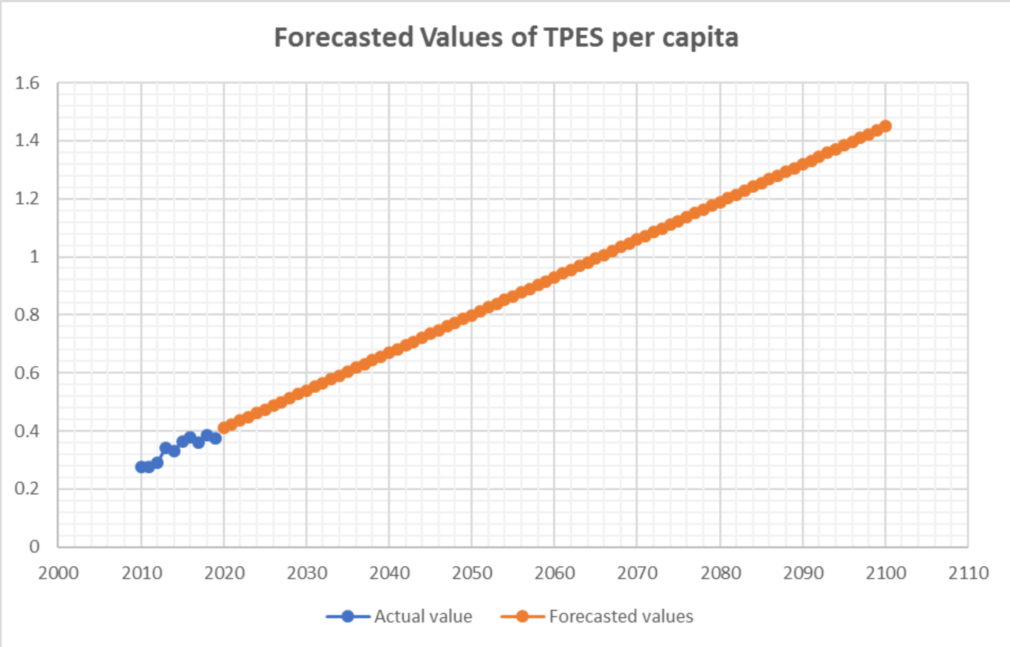


Figure 4-13: Total Primary Energy Supply Projections

Data source: Ghana Energy Commission, World Bank Group 2018

To make our modelling process of the total primary energy demand acceptable, we will make a few useful assumptions based on extensive literature on sustainable energy transitions.(Csala, 2016)

- Total energy demand will not continue to increase indefinitely, it will stabilize at a given maximum value. This maximum value is termed the "limit demand"
- As more renewables are integrated, the use of fossil will continue to decrease and the transport sector will experience huge reduction in energy use as a result of more efficient hybrid and electric vehicles.

Using these two assumptions, we will stabilize our TPES per capita and project the value of the TPES (Ktoe) starting from 2080, using projected population values from the world bank.

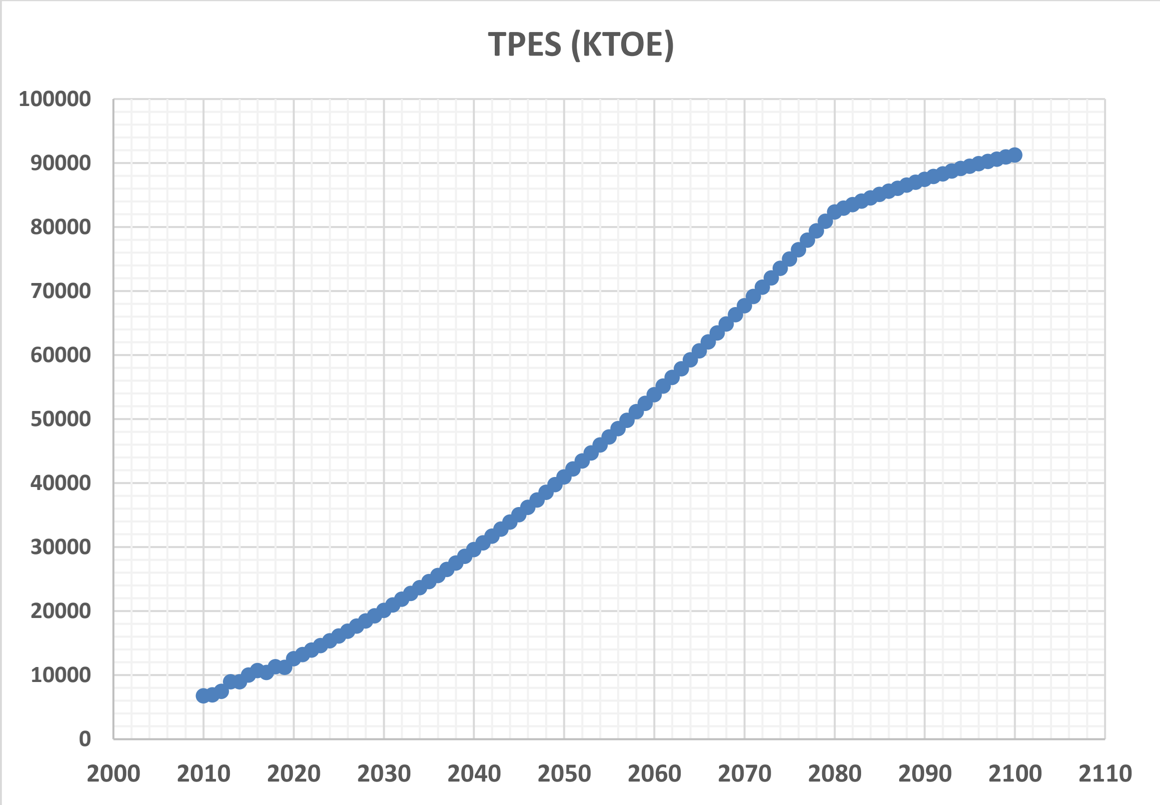


Figure 4-14: Total Primary Energy Forecast for Ghana (2010-2100)

Data Source: World Bank Group, Ghana Energy Commission.

4.3.2 Fossil Ultimately recoverable resource

The two fossil resources available in Ghana are natural gas and petroleum oil. (Ghana Energy Commission, 2017)

Table 4-5: Ultimately Recoverable Fossil Resource

Resource	Ultimately recoverable resource	Equivalent in GWh	Reference
Natural gas	0.8 trillion cubic feet	234480GWh	(Rhoda & Ardua, 2017)
Petroleum oil	1.08 billion barrels	1835390GWh	

4.3.3 Calibration of Parameters for dynamic EROEI of fossil

The EROEI is defined as a product of two parameters, the objective is to calibrate the variables

$$EROI = \varepsilon_k (1 - \gamma e^{-\xi p})\phi e^{-\psi p}$$

Equation 4-1: Dynamic EROEI

To calibrate the different values of the parameters used in the equation, we will proceed by a best fit using statistical data and projections from the world bank as well as other sources.
The following assumptions will be taken into consideration:

- The peak EROEI occurs at the peak fossil production
- Following the Hubbert production curve, this peak production should occur at

$$P_{max} = \frac{\ln(\varepsilon_k) + \ln(\varphi + \xi) - \ln(\varphi)}{\xi}$$

Equation 4-2: Equation for Maximum Extraction

- The EROEI falls to its minimum value when the resource is near or completely exhausted.

The variables used for the modelling process are obtained from various literature and also adjusted using best fit techniques to ensure the effectively capture the dynamics of the model.
The calibrated data used to run the model can be found at table 6-1 and 6-2

4.4 Renewable Energy Potential

The renewable energy potential of Ghana is classified as follows:
Solar Potential:
(Csala, 2016) established an exploratorium (Http://netset.csaladen.es/, 2018) from which the following technical potential are source as well as their resource quality.

Table 4-6: Solar Technical Potential and Resource Quality

Solar PV (1.5% land productivity, 10% efficiency)			Solar Thermal (6 hours of storage at 31MW/sqkm power density)	
Resource Quality distribution			Resource Quality distribution	
9	2.98TWh/year		5	313TWh/yr
8	285TWh/year		4	540TWh/yr
7	311TWh/year		3	178TWh/yr
6	107TWh/year		2	212TWh/yr

Table 4-7: Wind Resource Quality and Technical Potential

Resource Quality Distribution	Resource Availability
2	163TWh/year
1	614TWh/year

Our inputs in the stock and flow diagram uses energy and not power, so the wind potential in MW will be converted to TWh using capacity factor conversion method. According to (Asumadu-Sarkodie & Owusu, 2016), the capacity factor of 11 wind sites in Ghana were estimated for the good to excellent wind sites, the following results were obtained.

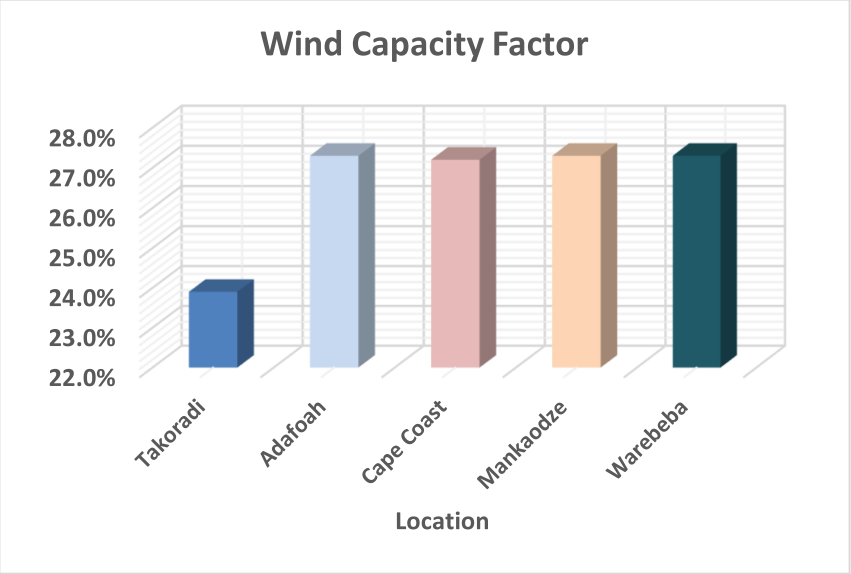


Figure 4-15: Wind Capacity Factor Ghana Best Sites

Source: (Asumadu-Sarkodie & Owusu, 2016)

The values of potential for wind, solar pv and solar csp will be used as inputs for the model to represent the technical potential of the renewable resource.

The data used for solar calibration of EROEI are included in the appendix Table 6-2

RESULTS AND DISCUSSION

The modelling of ERoEI was done for each of the available energy resources in Ghana. This section presents the results for the following energy resources:

- ✓ Natural gas
- ✓ Oil
- ✓ Solar
- ✓ Wind

Coal and geothermal were not used in the modelling process because these energy resources are not available in Ghana. The results of the modelling exercise for each energy resource will be presented and the average weighted result of each of the sub system (fossil and renewable) will also be presented. A comparative assessment of the resources and the sub systems will be analysed to draw meaningful conclusions for these results

5.1 Natural gas Results:

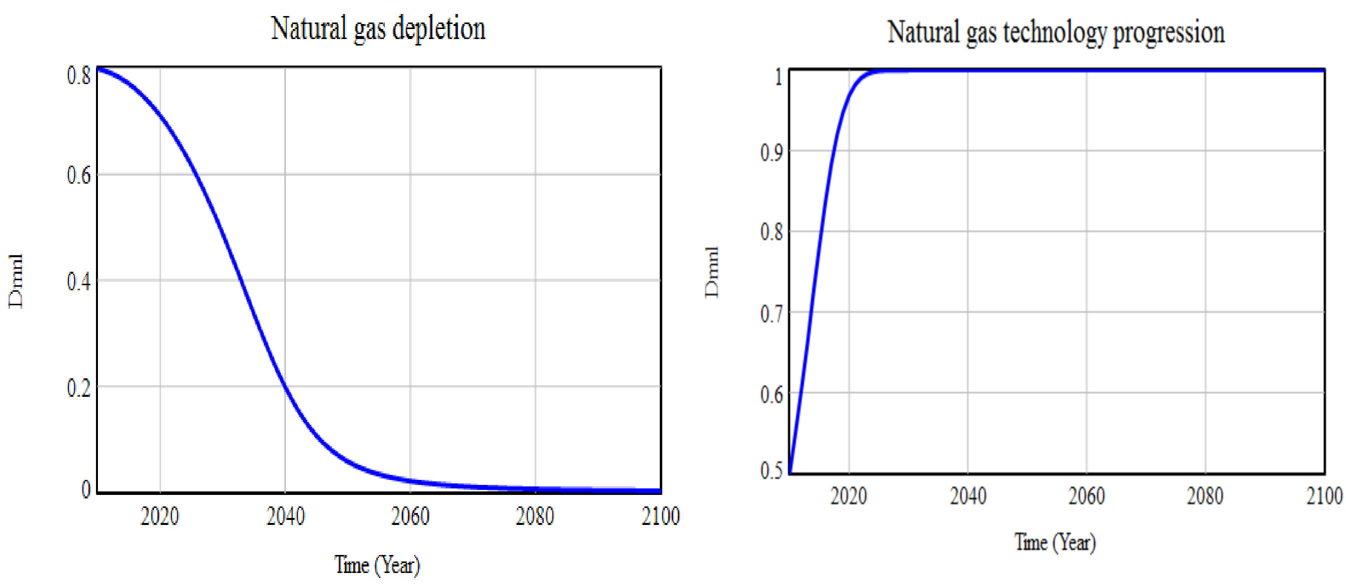


Figure 5-1:Natural gas parameters

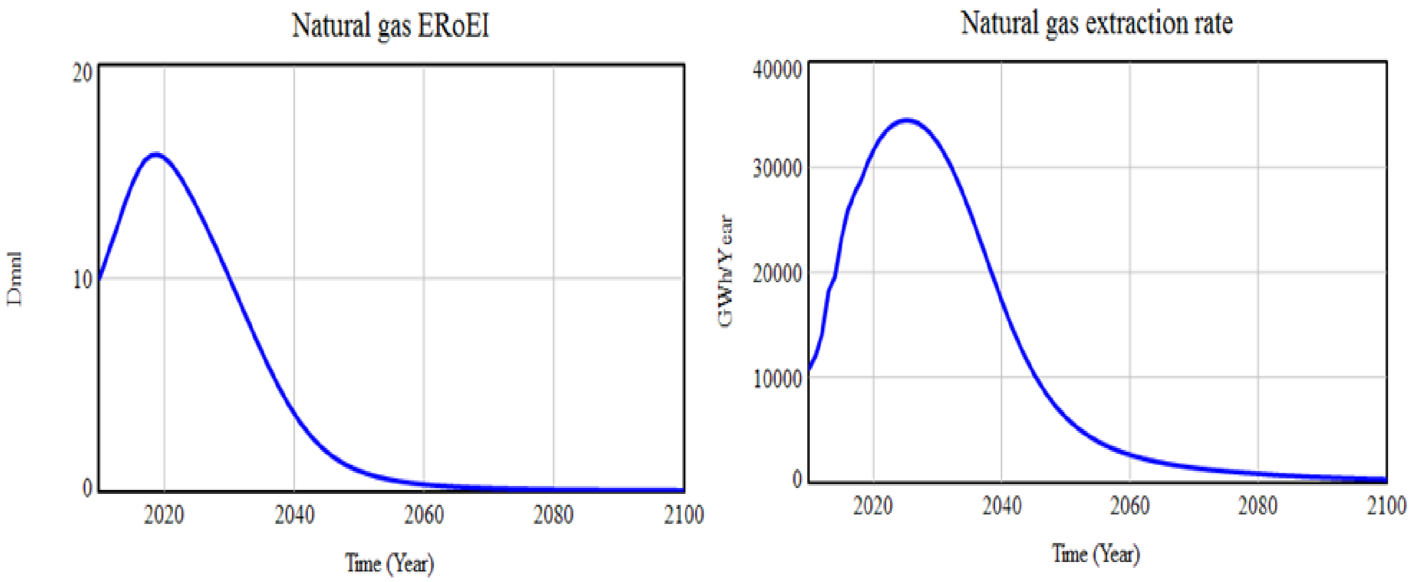


Figure 5-2: Natural gas ERoEI and extraction rate

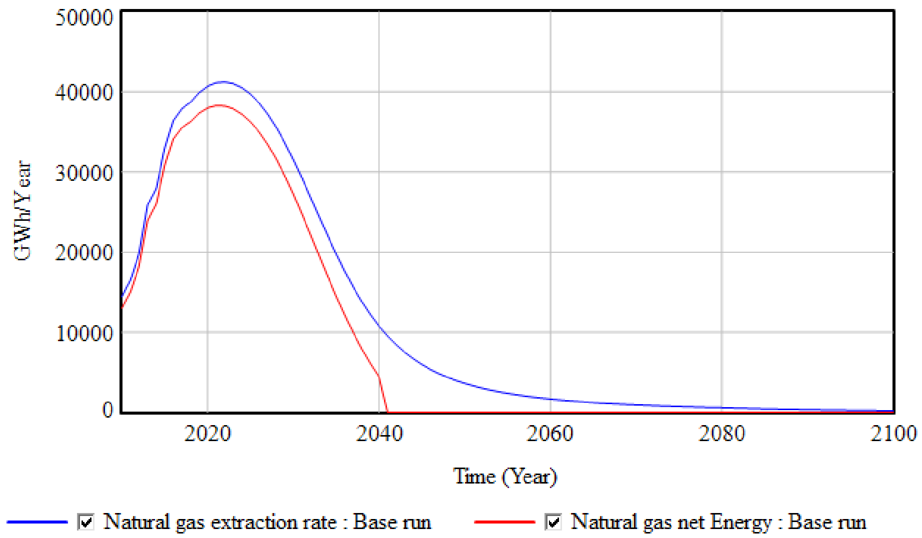


Figure 5-3: Natural gas extraction and oil net energy

5.2 Oil Resource Results

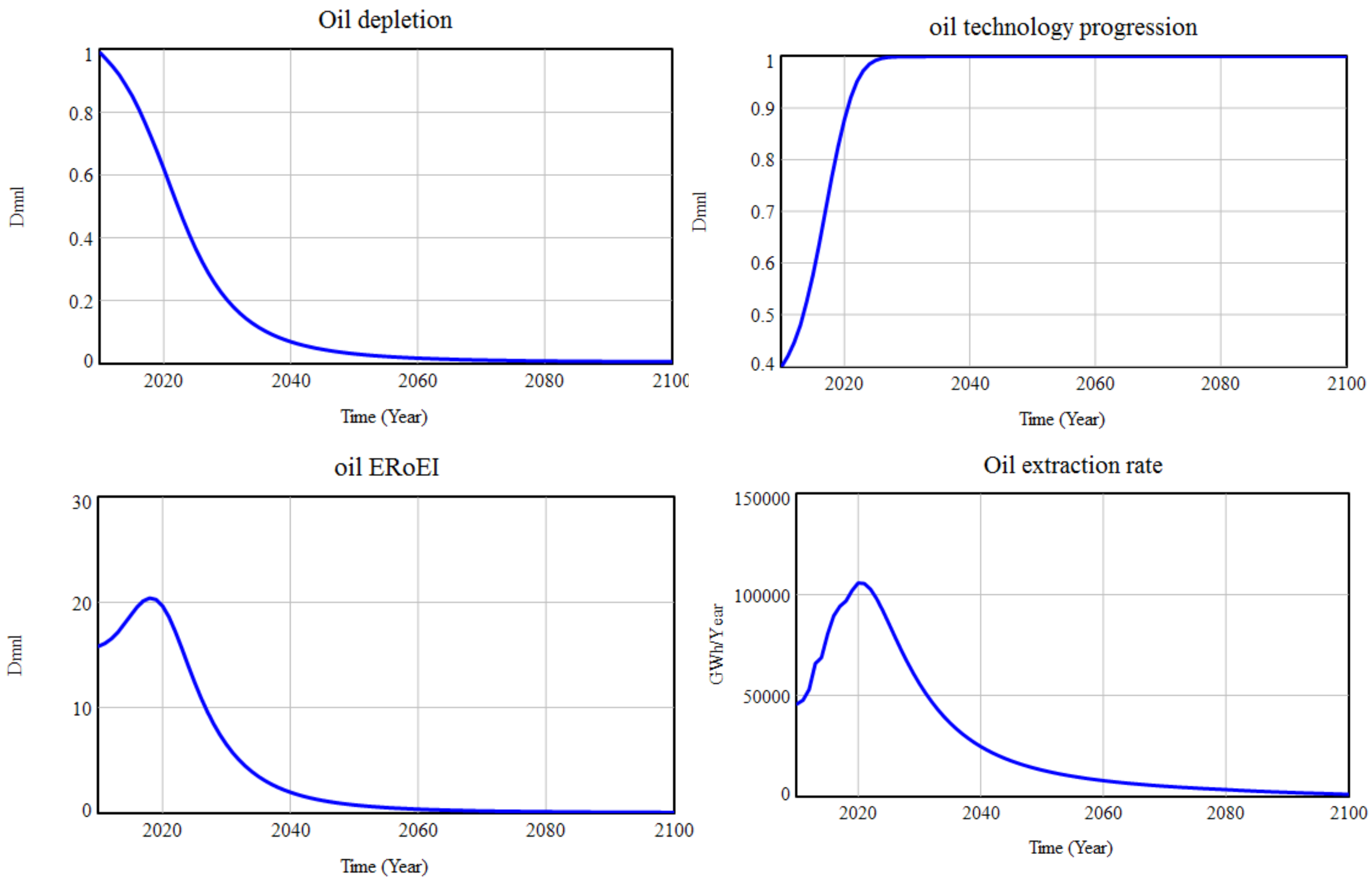


Figure 5-4:Oil parameter simulations

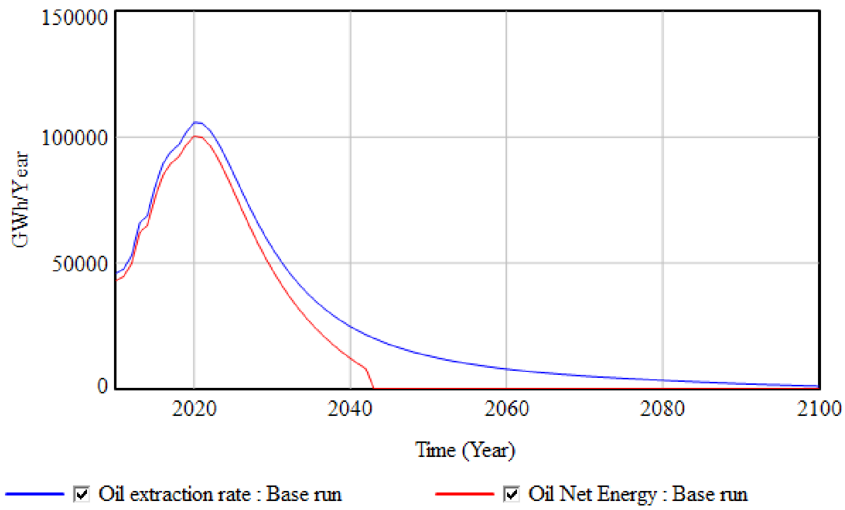


Figure 5-5: Oil extraction and net energy

Figures 5-1, 5-2, 5-3, 5-4 shows the different output of the modelling process of natural gas and petroleum oil. To make the interpretation of the results easy to understand and to allow for a comparative assessment of the figures above, a table will be used to explain for each variable of the model.

Table 5-1: Table of results for natural gas and oil

	Natural gas	Petroleum oil
Technology progression	Incept value of 0.5	Incept value of 0.4
Resource depletion	Incept value of 0.85 and becomes 0 at 2060	Incept value of 0.95 and becomes 0 at 2060
ERoEI	Incept value of 10 and peaks at 15 in 2020	Incept value of 15 and peaks at 20 in 2020
Extraction rate	Incept value of 10000GWh/year and peaks at 35000GWh/year in 2025	Incept value of 50000GWh/year and peaks at 10000GWh/year in 2020

Oil depletes faster than natural gas, this is because the demand for oil is higher than that of natural gas. Natural gas is mainly used in power plants for electricity production and as source of heat for industrial applications, domestic heating using natural gas is not required as Ghana doesn't experience very cold temperatures. The demand for oil is very high and is principally used in the transport sector. The net energy from oil and natural gas are expected to become zero as from 2040 necessitating a transition of the current Ghanaian energy system towards a more sustainable energy system.

5.3 Comparative Assessment of Fossil sub system

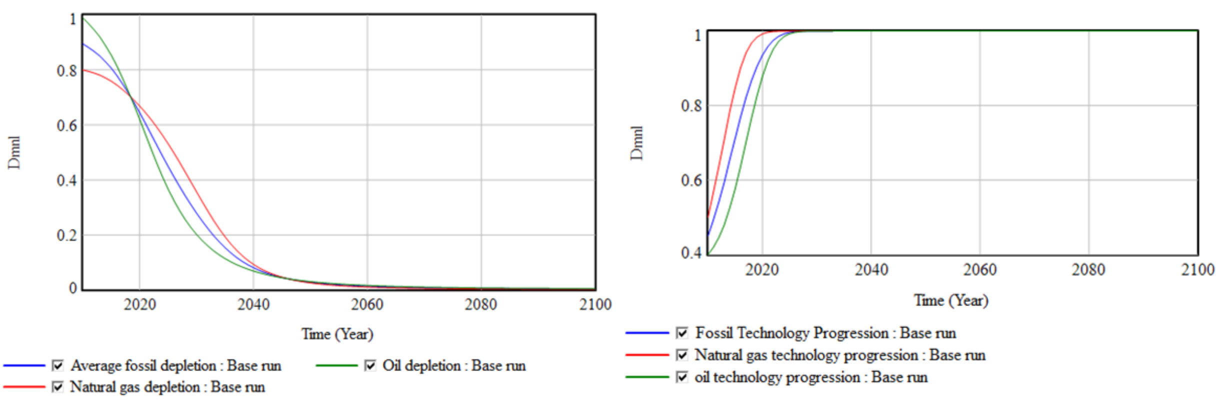


Figure 5-6: Technology Progression and Depletion of natural gas and oil

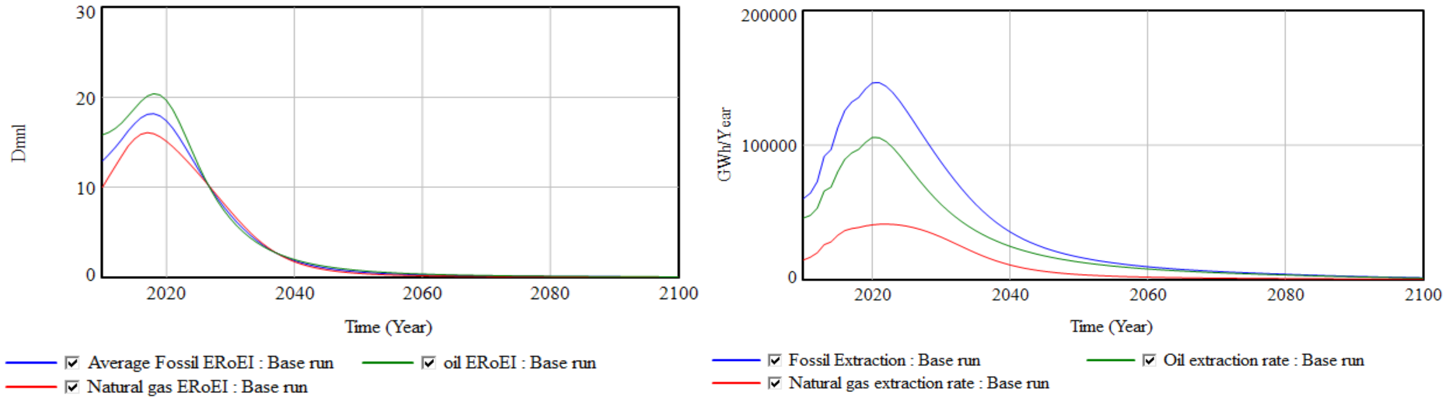


Figure 5-7:ERoEI and extraction rate

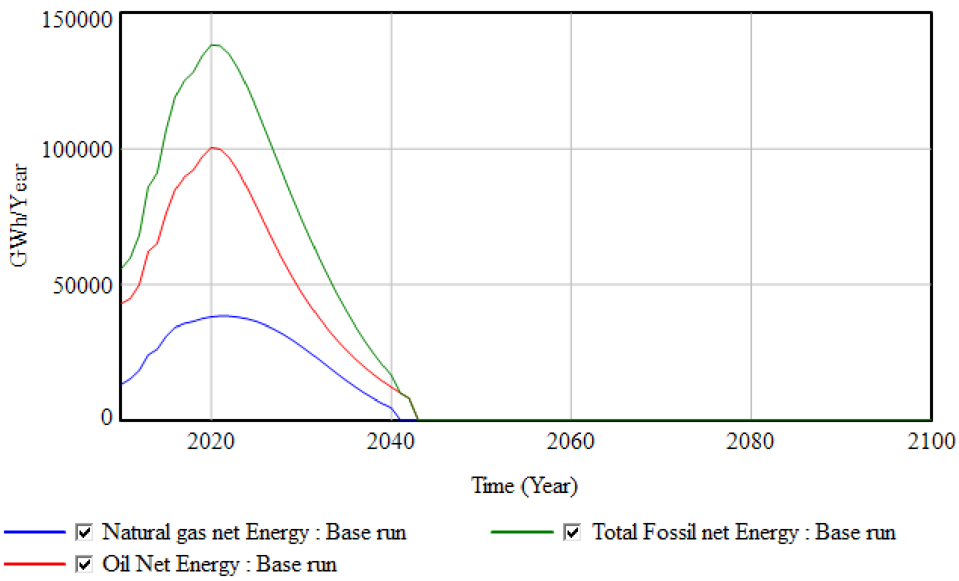


Figure 5-8: Net Energy for natural gas and oil

The fossil resource depletes quickly and after 2040, the fossil resources available and accessible become smaller and the fossil depletion attribute becomes asymptotic to zero. The technology progression grows steadily as more of fossil technology is deployed in the extraction process, the mastery and economies of scale permits the technological progression attribute to increase to a maximum value though never reaching full scale (100%) as there is always room for process efficiency improvement.

The results of the fossil EROEI shows an increase from the incept year (2009) and peaks a value of 15 at 2020. 2020 is therefore expected to be the year of maximum fossil extraction in Ghana after which the EROEI will begin to decrease.

Between the years 2010 and 2020, Ghana fossil extraction business is in the process of developing and exploiting new sites, so the EROEI will continue to increase until it will achieve its peak value at 2020, at this point, a lot of natural gas is being exploited to meet the new electricity infrastructure under construction. At peak EROEI of 15, there is maximum fossil (oil and gas) extraction in Ghana as seen on figure 5-6. According to the model developed for Ghana by the World Bank Group ((World Bank, 2013), fossil extraction in Ghana is expected to peak between the years 2019 and 2020. The values obtained from SD modelling of the fossil resource EROEI depicts a similar trend of maximum fossil extraction at 2020.

The fossil demand which is the amount of fossil being used in the Ghana will depend on the EROEI of the fossil resources, as the fossil process extraction begins to become more prominent, more of fossil is being consumed as the EROEI increases and this consumption begins to fall gradually as the EROEI starts to decrease. In this case, as the EROEI starts decreasing, there availability and the ease of obtaining the fossil becomes low and therefore, the demand falls favouring a transition to renewables.

Unlike conventional modelling approaches, fossil demand in this case of system dynamic modelling doesn’t continue to grow indefinitely, its growth is regulated by the return on energy investments. As this return falls, the energy mix comprises of lesser fossil demand. The peak fossil demand for Ghana is 140000GWh/year. The research excludes the fossil fuel imported and exported, it is assumed all the fossil will be used by the country to meet its demands, the effects of imports and exports is beyond the scope of this thesis.

The net energy which is the amount of energy available to the society is shown on figure 5-7. At lower values of EROEI, the net energy available to the Ghanaian community becomes zero and the fossil resources are completed depleted or now act as energy sinks requiring more investments in terms of energy than the output energy they can produce. After 2040, fossil fuel extraction under a current normal demand scenario becomes unprofitable as the net energy becomes zero.

5.4 Solar Resource:

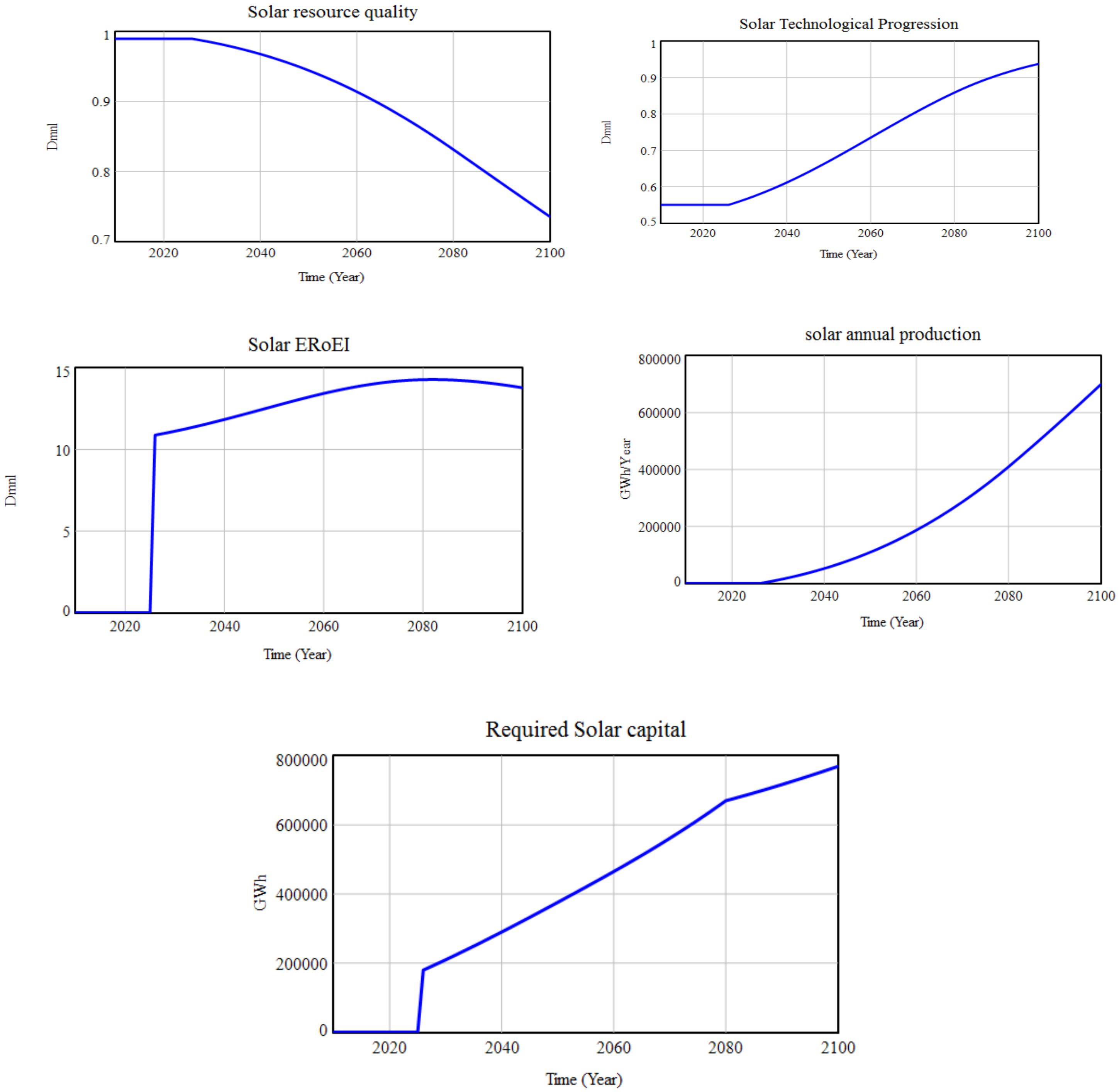


Figure 5-9:Solar Simulation Results

5.5 Wind Resource:

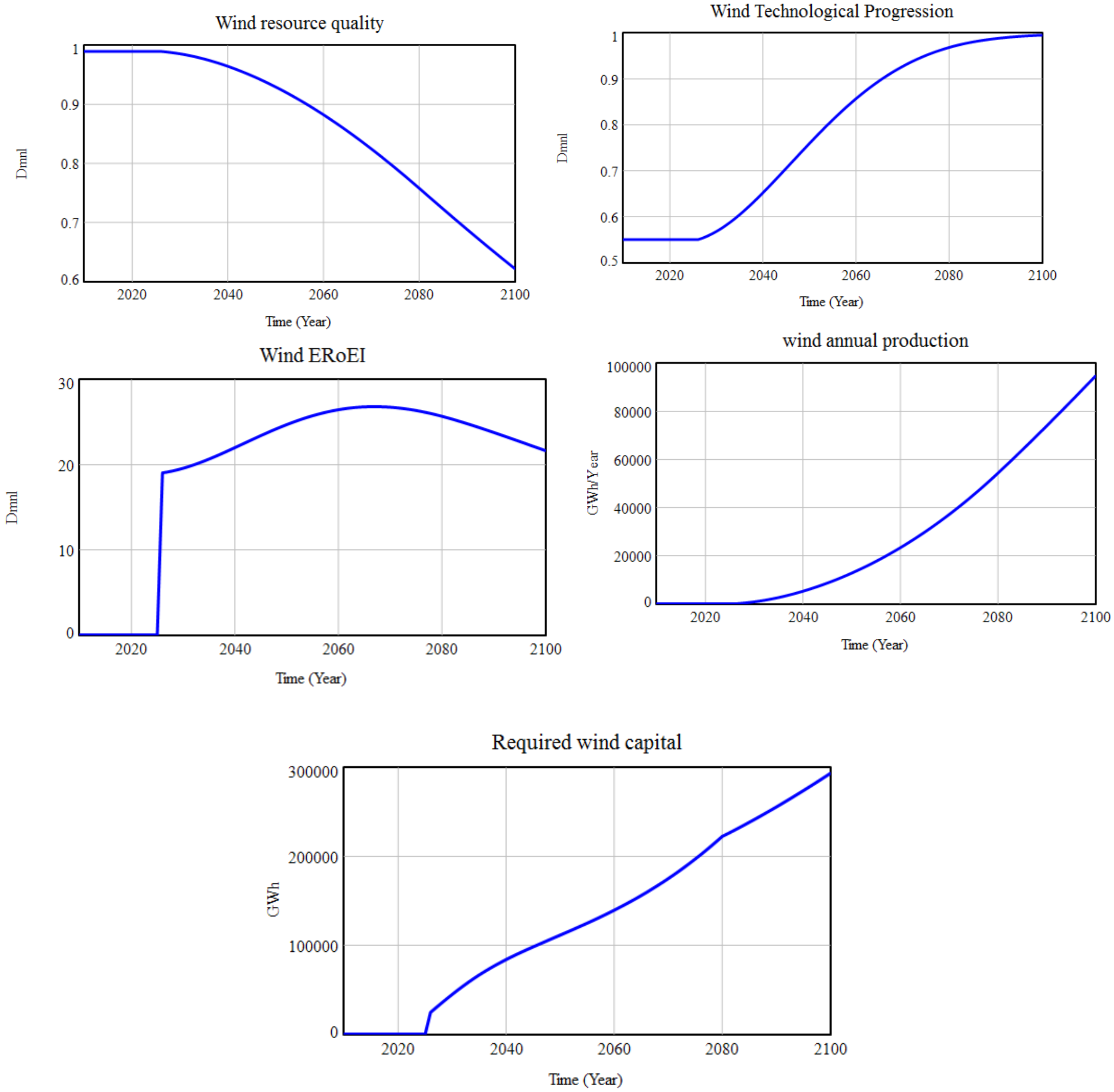


Figure 5-10: Wind Simulation Results

Solar and Wind have similar behaviours for all the variables used in the model, the only significant difference between the two resources is the magnitudes of the variables obtained as output of the modelling process. Solar has a higher technical potential than wind in Ghana but a low ERoEI compared to wind. However, due to the large technical potential, solar generation is expected to be the major resource that accounts for large energy generation and supply under the sustainable transition strategy.

5.6 Renewables Comparative Assessment

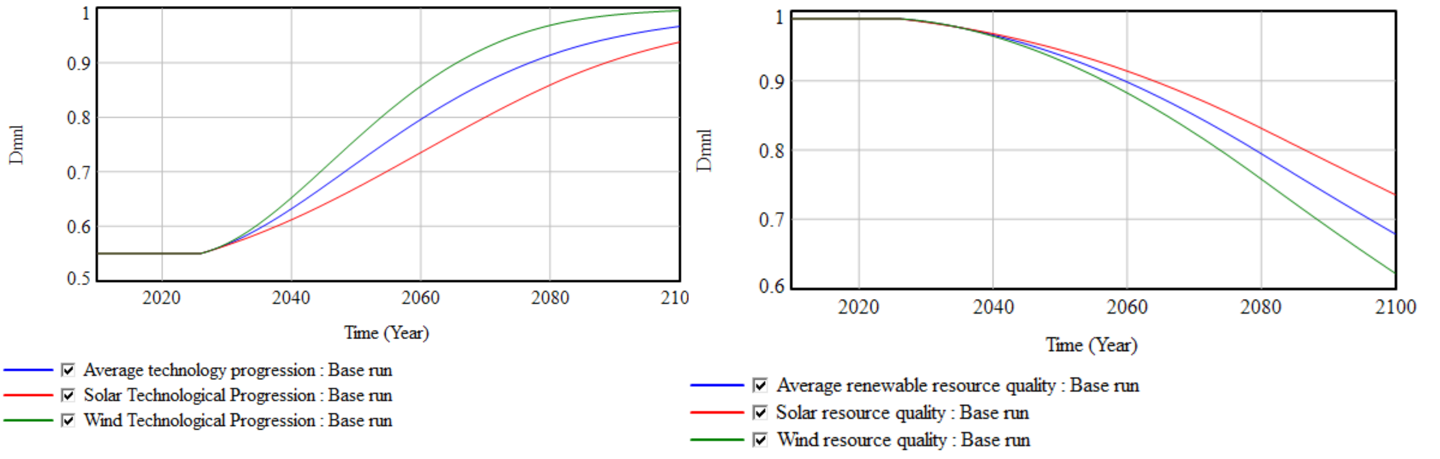


Figure 5-11: Technology Progression (a) and resource quality(b)

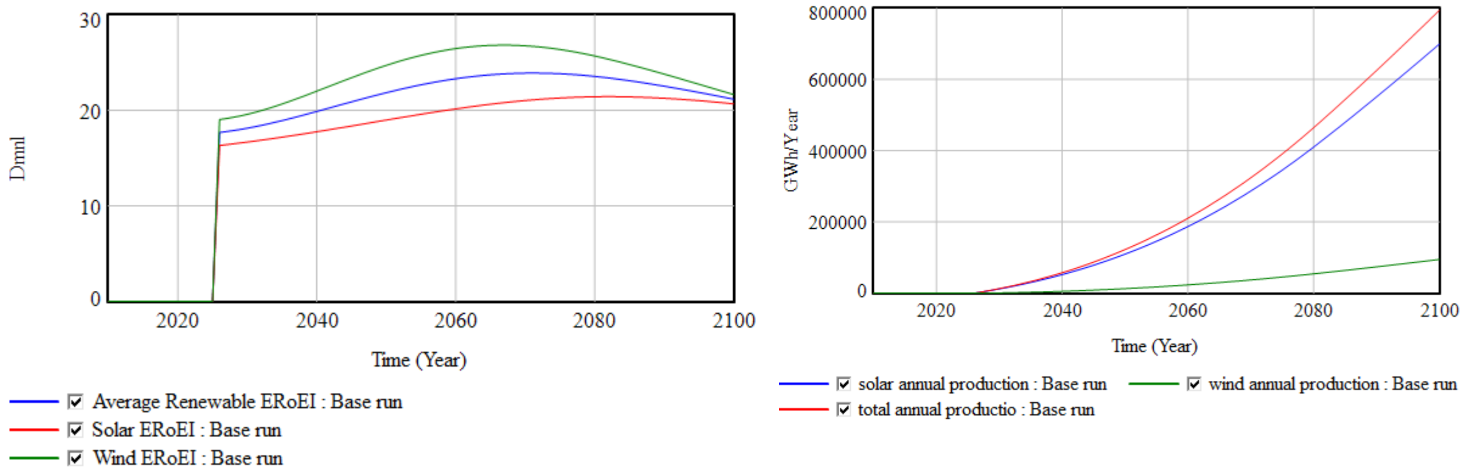


Figure 5-12: Renewable ERoEI (a) and Renewable annual production (b)

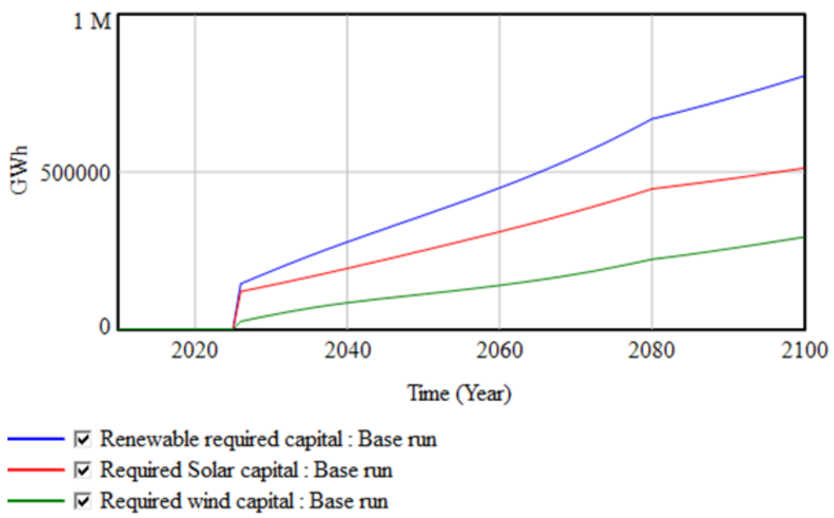


Figure 5-13: Renewable required capital

The resource quality for RE which is analogous of fossil depletion shows a decrease, however, as shown in the different figures above, this decrease is not very significant. The resource quality measures the decrease in the number of potential good sites available for renewable power installation and development. The value of the resource quality can never be zero because unlimited scale renewable energy resources (Wind, Solar) have a technical potential far greater than the demand of the country, so the resource quality will decrease insignificantly because of this effect of very high technical potential. The resource quality is the key attribute of a sustainable energy resource.

The variation of the technology progression shown in Figure 5-8 explains renewable energy technologies are still very low in general and the deployment in Ghana as of 2018 is still very low, but as the demand for RE continues to increase as a result of a decrease in fossil availability, the economies of scale and technology mastery (efficiency of solar PV for example) will begin to increase globally as well as in Ghana, technology progression is expected to become significantly important by the year 2040.

Contrary to the fossil EROEI, the renewables EROEI for Ghana shows a constant increase up to the years 2060 before level at a constant value of 19. This shows the sustainability of renewables as they constantly have an increasing EROEI and never experience a decreasing trend unlike the case of fossil. The renewable EROEI is the core of this thesis as it shows the importance of deploying and integrating scale unlimited renewables (wind, solar) in the energy system mix. The case for Ghana, the EROEI shows renewables will constantly be profitable and beneficial to develop even at 2100. Between 2010 and 2020, the RE EROEI is zero because no renewable sites (solar and wind) have been developed, and the returns on investments will become significant when the renewables will come into deployment. The approach adopted in formulating this model is based on the policy of the Ghanaian government to have 10% renewables in the electricity mix by 2020. We therefore under a “if” clause, model the start (incept year) of renewables as from 2020. However, to allow for comparative assessments between the fossil and the renewable system, the incept year for the both technologies are assumed to start from 2010, however, renewable will then show a zero EROEI until 2020 where its EROEI will correspond the average weighted minimum EROEI of solar and wind as reported by (Csala, 2016).

The sustainable transition strategy for Ghana in thesis is oriented towards replacing the present fossil with scale unlimited renewables (Wind, Solar). Though hydro is presently very significant in Ghana, the hydro sites are almost exhausted and hydro cannot carter for further demands, so the interest is to evaluate through the values of EROEI how much of wind and solar can support further energy demands in Ghana.

In our system dynamic analysis, we modelled in addition to the EROEI, other important factors like the annual production which will be required from wind and solar and also the required capital investments (in energy units) which will be needed to develop these renewable energies. Figure 5-11(a) shows graphs of renewable energy annual production and figure 5-12 shows the energy investments needed by Ghana under the sustainable transition strategy of renewable integrations.

Just like the EROEI, the annual production is zero until renewable integration starts in 2020, in this system dynamic model, we considered energy demand as an exogeneous variable and therefore the annual production shown in figure 5-11 (a) is under the assumption that the population can afford the energy, however, this is not always the case as the production depends on many variables which are economically and depend on profits and loss statements of the companies generating the power. However, endogeneous energy modelling which considers that demand is affected by variables within the system was beyond the scope of this thesis.

5.7 Comparative Analysis of RE and fossil subsystems

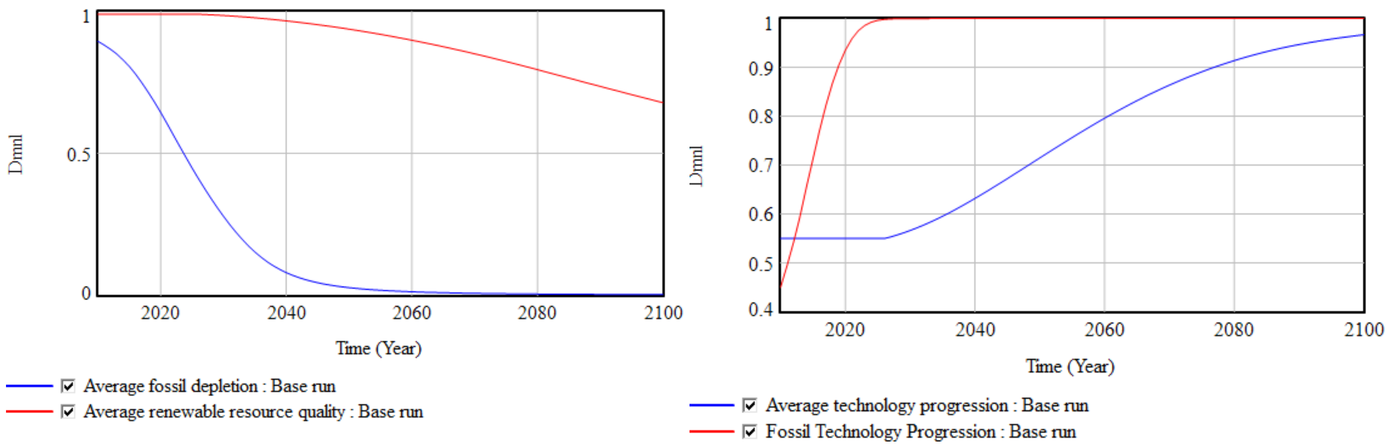


Figure 5-14: Comparative assessment of fossil and renewable, technology progression and resource quality (depletion)

The resource depletion of fossils in Ghana is very rapid, this is due to the fact that the ultimately recoverable resources are not in large amounts and therefor a high dependence on fossils as is the present case with Ghana leads to a quick exhaustion of the resources. Unlike fossils, renewables have a decrease in resource quality which is not very significant, though the number of potential good sites reduce, the technical potential remains greater than the annual demand.

The technology progression of fossils is very quick, fossil is a well-established technology and transfer of fossil technology is a fast process. Ghana has easily acquired the fossil technology unlike renewable technology which is expected to grow slowly under the transition strategy.

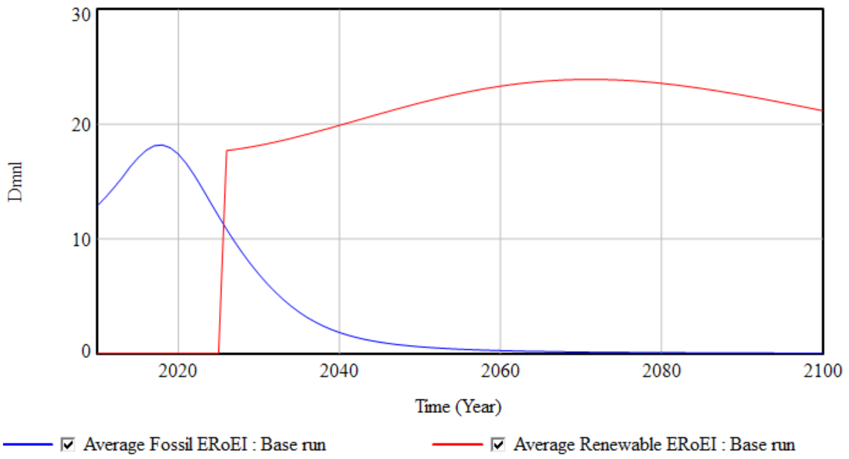


Figure 5-15: Comparative assessment of renewables and fossil

Fossil fuels have a relatively higher ERoEI, however, the dynamics will not stay the same, as fossil resources continue to deplete, the transition to renewables in Ghana will become an absolute necessity if the nation was to meet its continuous growing demands. The long-term simulations of the values of ERoEI discourages the development of fossil in Ghana, which is however still in the process and heavily supported by the government. Renewables will create a sustainable energy resource for Ghana observing the long-term trends of the ERoEI.

The sensitivity analysis of the different variables of the simulation can be found in the appendix (Figures 8-1, 8-2, 8-3, 8-4). This sensitivity analysis is done by changing the exogeneous demand function to obtain the behaviour of the intervening variables of the model. The following conditions are used for the sensitivity analysis:

- **low demand**: the results for this scenario are obtained by running the module with a demand ratio 0.7 times the base run. This scenario is obtained if the projected energy demand were to reduce by 30%.
- **High demand**: This scenario is a high demand ratio simulation for the projected energy increased by a 50%. (demand ratio is 1.5 times the base run)

CONCLUSION

The focal point of this research was to integrate the EROEI function as a key metric in energy planning processes through a system dynamic approach. We have successfully developed timeseries of changing EROEI for the fossil and renewable subsystems and have shown the dynamics of the EROEI of renewables and fossil. It is observed from our modelling and simulation process that, the EROEI of renewables increases gradually but achieve a constant or stable value through to the end of the century starting from the year 2060. However, the fossil system has a very quick EROEI and suddenly decreases as the fossil resources become depleted.

The objectives of the research were:

- Show how ERoEI metric can be used to assess among different technologies which ones are sustainable and preferential according to the trends of the ERoEI. By so doing, it is possible to integrate renewables and simultaneously combat GHG emissions from fossil.
- Incorporate ERoEI as key metric in energy planning studies.
- Help national energy planners to integrate Net Energy Models in their planning mechanisms and not to only focus on the profit and loss models.

To achieve the following objectives, we developed a system dynamic model using Vensim and evaluated a timeseries of EROEI as well as associated variables that affect or are affected by the dynamics in the EROEI. From literature, we established that for an energy resource to be termed sustainable, it should have an EROEI which is constantly increasing with time or the worst stay constant.

We evaluated from our Vensim simulation the following:

- ERoEI for natural gas and the annual extraction
- ERoEI for oil and the annual extraction
- ERoEI for scale unlimited renewables (wind and solar), their annual required wind capital and their annual production expected to meet the energy demands as fossil depletes.

The approach used in the thesis is a biophysical modelling contrary to standard econometric analysis and computable generatable equilibrium modelling. The thesis avoided considering the effect of price or the profits and loss statements on the energy dynamics but concentrated on evaluated the quantity of energy resource is available for Ghana and how much time will this resource available last given the energy demand scenarios evaluated in the scenario analysis. In addition, the thesis also looked at if the exploitable resources will remain profitable over the years. The dynamics of resource available and resource use is very complicated and interrelated, which justifies the use of systems dynamics in the research.

The results of the simulation for scale unlimited resources (wind and solar) proved they had an EROEI which increased over the years and stay constant up to the end of the century while fossil resources showed an EROEI which grow quickly to a peak value and collapsed afterwards.

The significance of this study is to aid energy planning institutes on the priorities of energy infrastructure developments owing to the dynamics of the energy return on investments. In the case of Ghana where the government is planning to expand thermal plants, our results show though this a workable solution for the moment, it will not be a suitable and sustainable solution in the long term as the energy return on investments for natural gas and oil are expected to fall rapidly after 2020 and consequently a depletion of the fossil resources is expected to occur by 2040.

The recent development of thermal plants as a result of the fossil available is then an “evil gift” as it works for a moment and becomes too expensive to run as the returns on investments become critically low in the long term.

As fossil resources are expected to deplete, what then is the future of renewables in Ghana and how can a transition be structured to ensure the energy demands which continues to increase on a yearly basis are met by renewables? To answer this, we evaluated the required solar and wind capital in energy units required to develop the energy system in Ghana.

Solar potential in Ghana is very high and solar technology will be the main energy resource for the country for a sustainable transition process. Wind too has a considerable potential but with a low resource quality, however, wind technology remains crucial to Ghana.

We therefore recommend the government of Ghana to quickly implement policies that will accelerate the development of scale unlimited renewables and increase high integration and penetration of renewables. This planning and assessment of ERoEI as well as the strategies to transit from a fossil-based system to a more renewable based system should therefore be an inclusive and integral process involving all the stakeholders of the energy system and financial (money streams) as well.

The challenge of the modelling process was the limited historical data for fossil and renewables to permit an accurate calibration of the model. Fossil extraction in Ghana has only been operational for 8 years and the amount of data for these years is not sufficient. Also, the no access to investments in the oil and gas industry for exploration and exploitation was also a hindrance to the modelling process. However, a key objective of the modelling was to create a dynamic interaction between the ERoEI, the available resources and the net energy as well.

The results obtained for the extraction of fossils are similar to the extraction simulated by the world bank

Also, as future perspectives, we recommend a system dynamic study of the EROEI of each of the fossil resource (natural gas and oil) and for the renewables (wind and solar) to have a more detailed understanding on the behaviour of each resource in the entire energy mix.

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APPENDICES

8.1 Parameters for fossil EROEI

	γ	ϕ
Natural Gas	0.99	0.99
Petroleum Oil	0.99	0.99
Average fossil value	0.99	0.99
Reference /explanation		(Rhoda & Ardua, 2017) Oil and gas exploration began in Ghana in 2009, so the virgin resource is still abundant (less than 1% exploited)

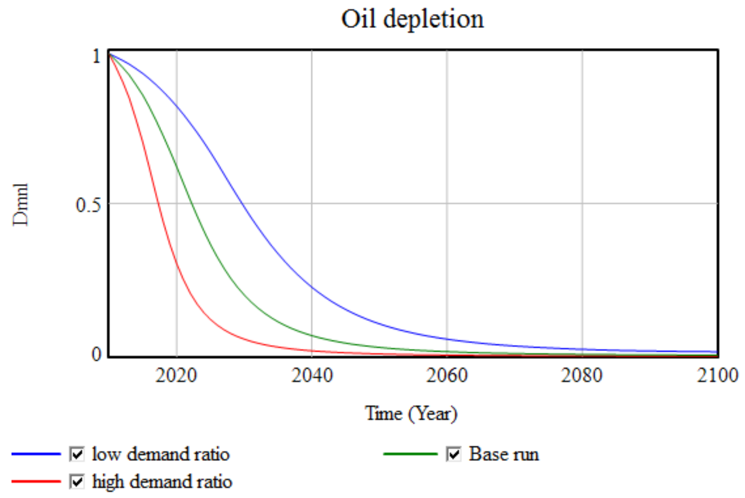
8.2 Parameters for Renewable EROEI

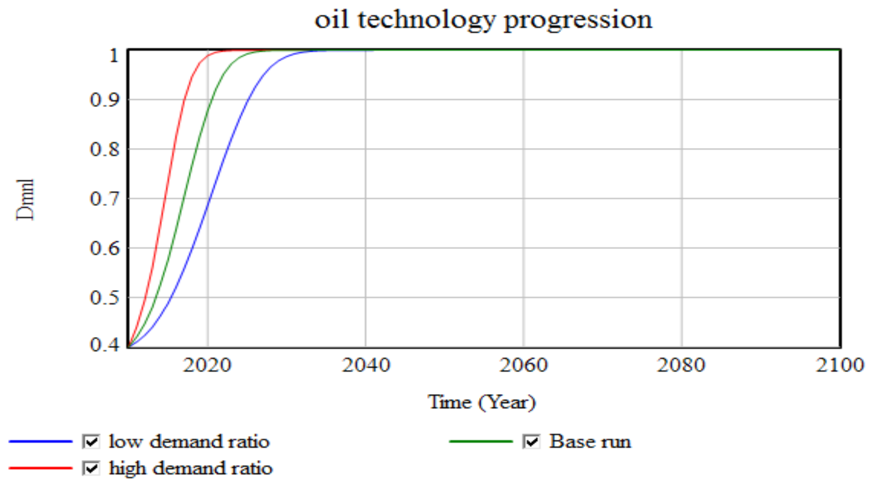
	Renewable System Variables Parameterisation				
	ε_k	γ	ξ	ϕ	ψ
Solar PV	17.65	0.97	0.04	0.99	0.01
Wind	20.18	0.98	0.02	0.99	0.01
Average fossil value	18.92	0.975	0.03	0.99	0.01
Reference /explanation	(Csala, 2016)	Best fitting values obtained from multiple simulations	(Csala, 2016)	Technical resource evaluation	(Csala, 2016) Best fit values from model calibration

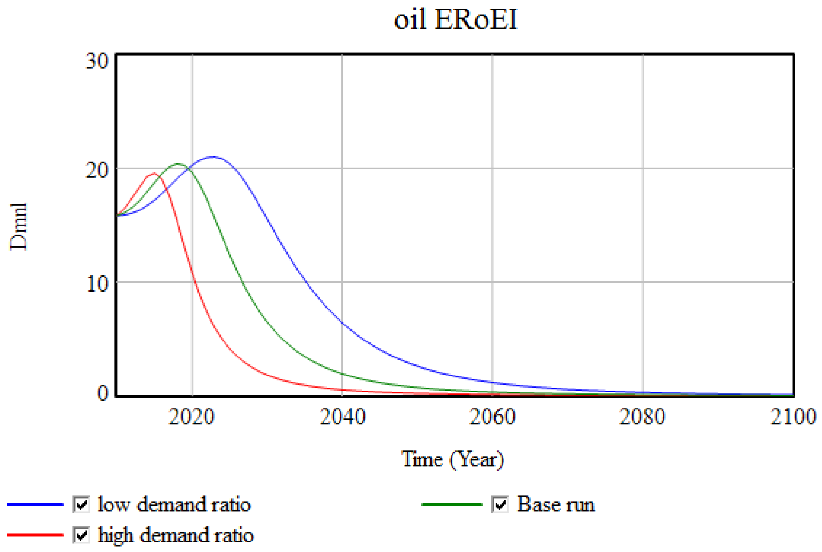
8.3 Energy Statistics

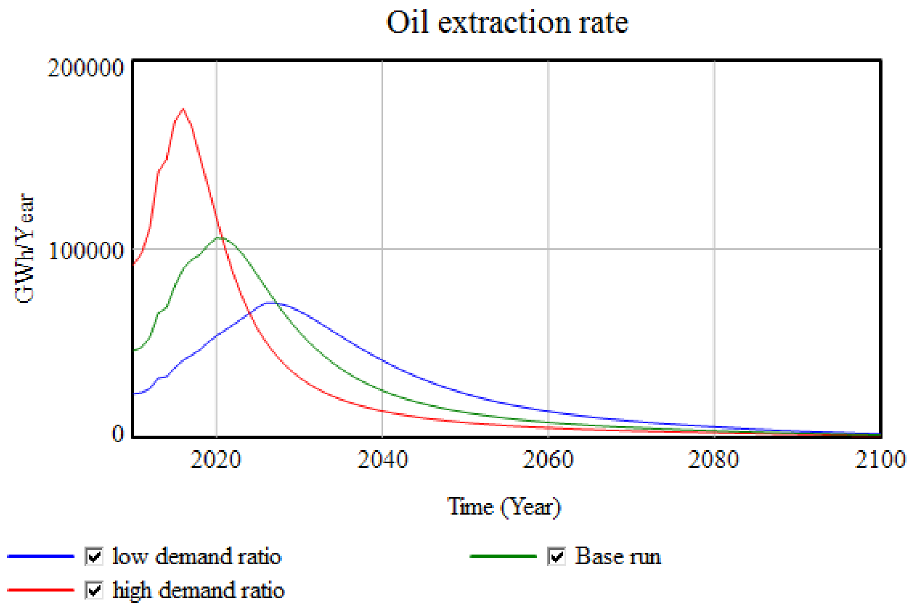
Energy Indicator	Unit	2007	2008	2009	2010	2011	2012	2013	2014	2015[1]	2016
Total Primary Energy Supply	KTOE	6,404	6,273	6,036	6,946	7,609	8,362	8,564	9,147	9,550	9,521
Total Final Energy Consumed	KTOE	5,255	5,184	5,706	5,630	6,174	6,613	6,894	6,983	7,162	7,106
Total Electricity Generated	GWh	6,978	8,324	8,958	10,167	11,200	12,024	12,870	12,963	11,492	13,022
Total Electricity Consumed	GWh	6,214	6,913	7,154	7,844	8,976	9,905	10,636	10,695	9,685	11,418
Total Petroleum Products Consumed	KTOE	2,127	2,071	2,598	2,491	2,827	3,318	3,422	3,377	3,545	3,320
Total Biomass Consumed	KTOE	2,594	2,518	2,493	2,464	2,576	2,589	2,676	2,792	2,785	2,804
Population	million	22.3	22.9	23.4	24.7	25.3	25.9	26.5	27	27.7	28.3
GDP (Constant 2006 prices)	million Ghana cedis	19,913.4	21,592.2	22,336.0	24,101.0	27,486.0	30,040.0	32,237.0	33,522.0	34,808.0	36,016.0
Energy Intensity of the Economy	TOE/GHS 1,000 of GDP	0.26	0.24	0.26	0.23	0.22	0.22	0.21	0.21	0.21	0.20
Total Energy Consumed/capita	TOE/capita	0.24	0.23	0.24	0.23	0.24	0.26	0.26	0.26	0.26	0.25
Total Electricity Generated/capita	kWh/capita	312.9	363.5	382.8	411.6	442.7	464.2	485.7	480.1	414.9	460.2
Total Electricity Consumed/capita	kWh/capita	278.7	301.9	305.7	317.6	354.8	382.4	401.4	396.1	349.6	403.5
Total Petroleum Products Consumed/capita	TOE/capita	0.10	0.09	0.11	0.10	0.11	0.13	0.13	0.13	0.13	0.12
Total Biomass Consumed/capita	TOE/capita	0.12	0.11	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Total Electricity Consumed/GDP	kWh/GHS 1,000 of GDP	312.0	320.2	320.3	325.5	326.6	329.7	329.9	319.0	278.2	317.0
Total Primary Energy Supply/GDP	TOE/GHS 1,000 of GDP	0.32	0.29	0.27	0.29	0.28	0.28	0.27	0.27	0.27	0.26
Total Petroleum Products Consumed/GDP	TOE/GHS 1,000 of GDP	0.11	0.10	0.12	0.10	0.10	0.11	0.11	0.10	0.10	0.09
Total Primary Energy Supply/capita	TOE/capita	0.29	0.27	0.26	0.28	0.30	0.32	0.32	0.34	0.34	0.34
Grid Emission Factor (wind/solar projects)	tCO2/MWh	0.41	0.41	0.41	0.35	0.32	0.35	0.51	0.32	0.28	0.39
Grid Emission Factor (all other projects)	tCO2/MWh	0.58	0.56	0.57	0.51	0.44	0.48	0.73	0.36	0.31	0.43

8.4 Sensitivity Analysis for Oil

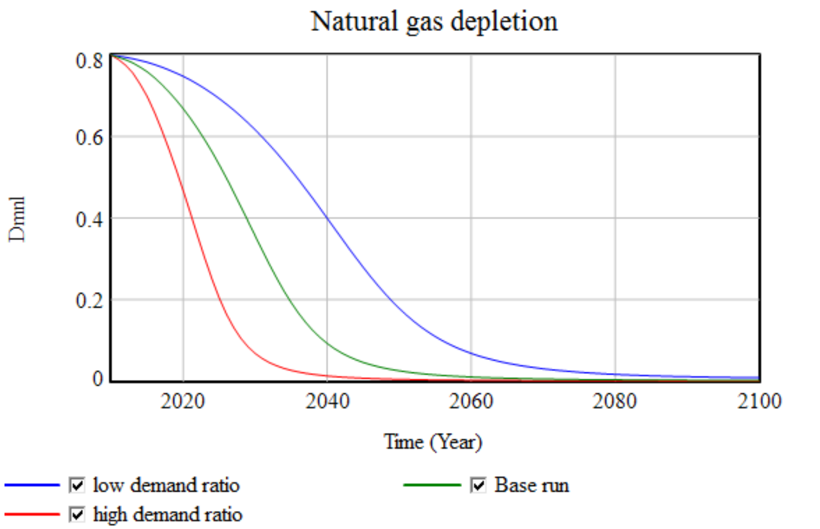


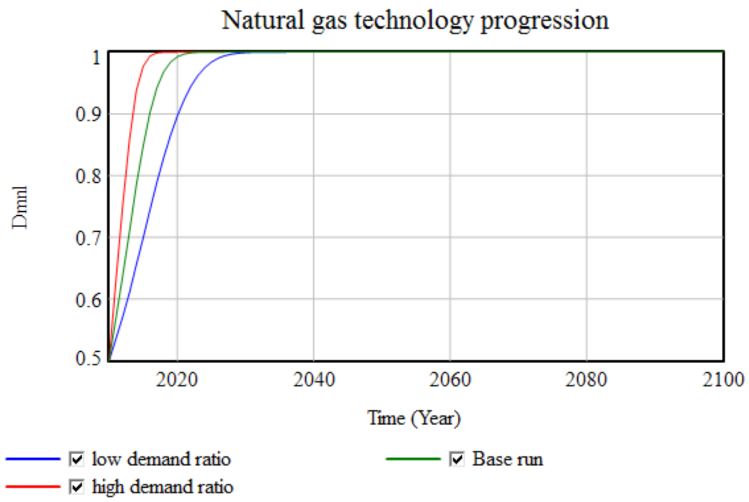


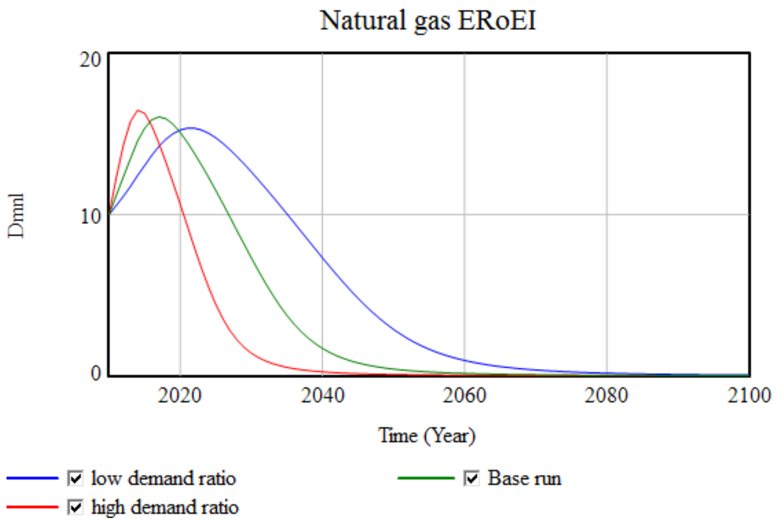


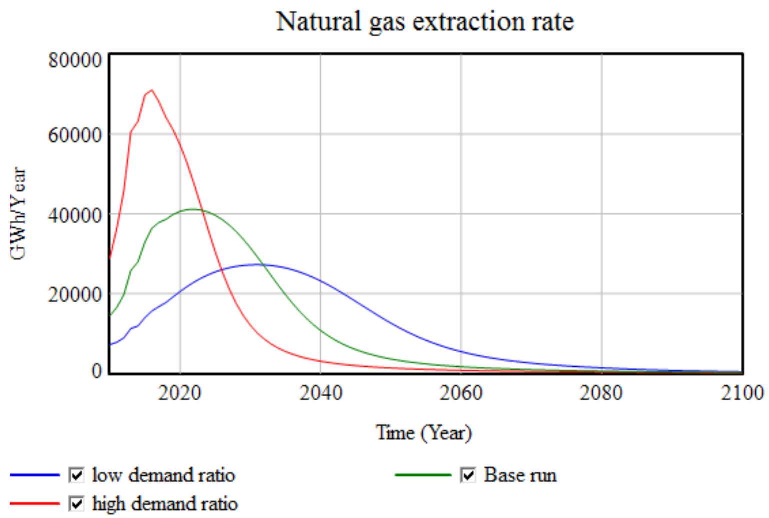


8.5 Sensitivity Analysis for Natural Gas

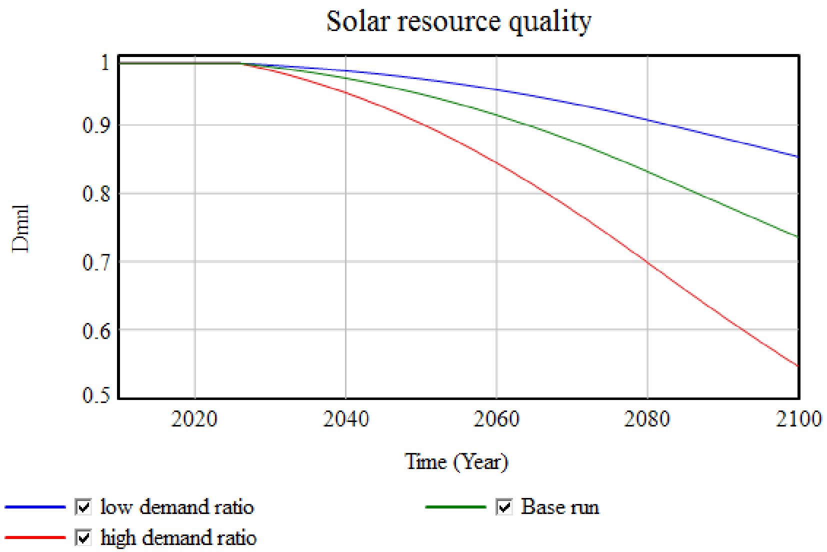


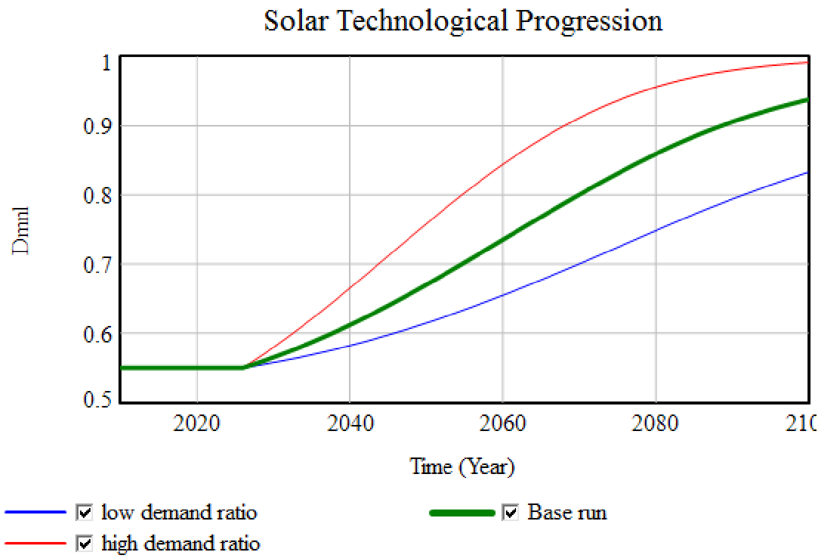


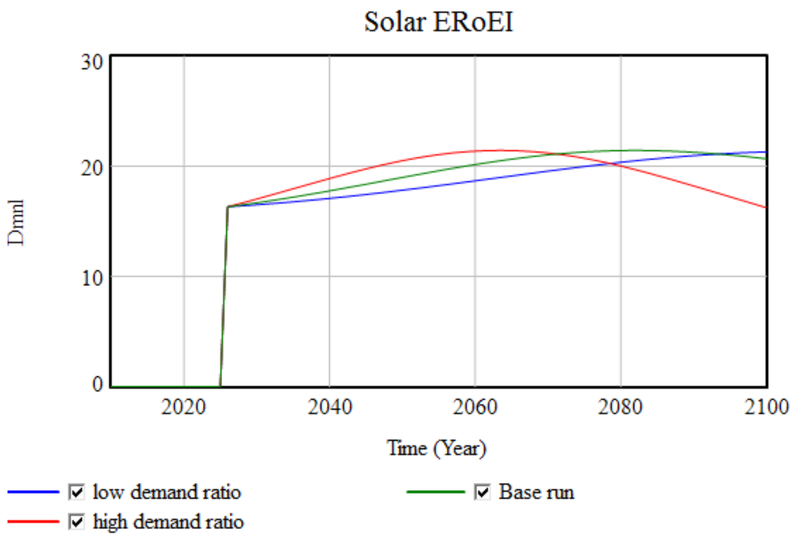


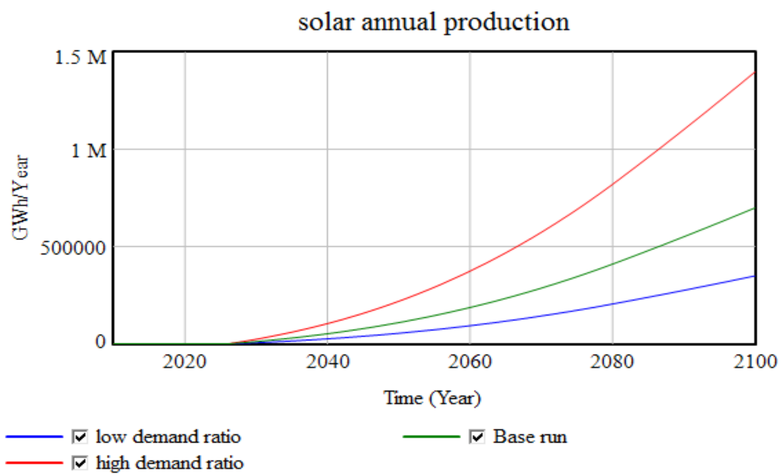


8.6 Sensitivity Analysis for Solar

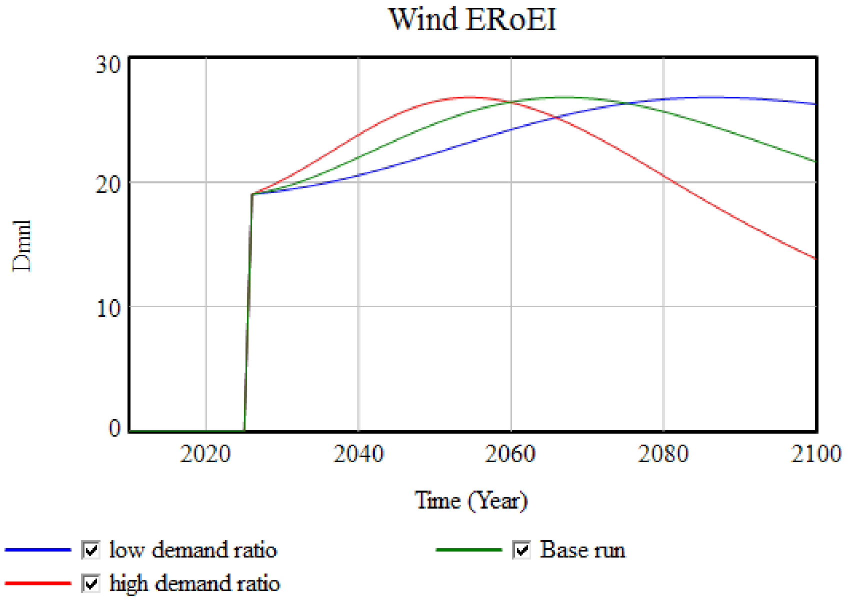


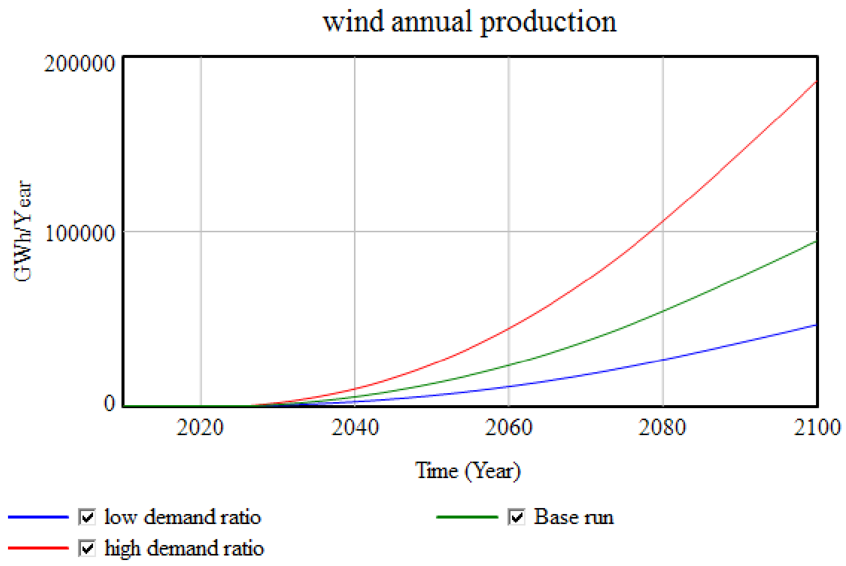


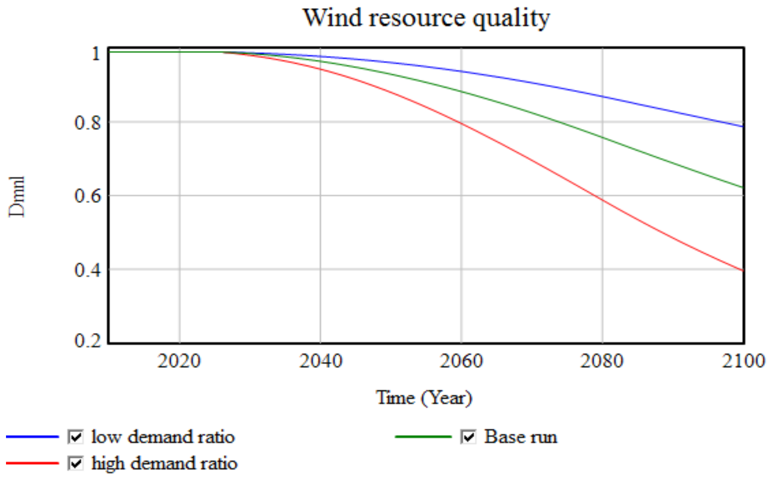


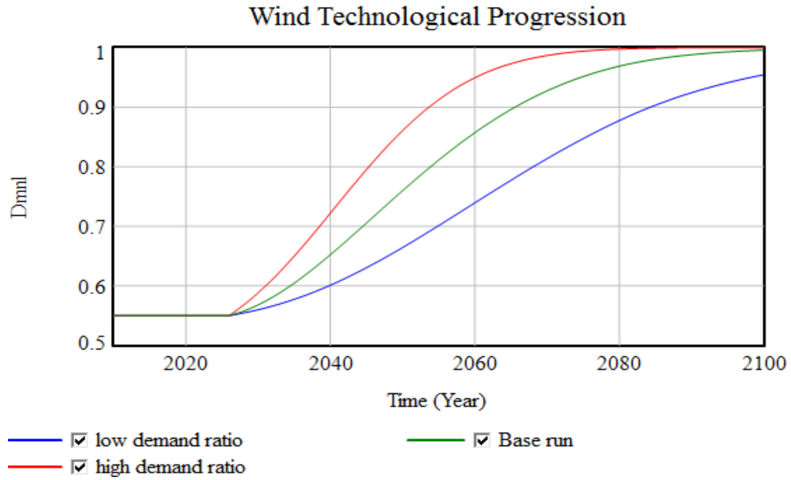


8.7 Sensitivity Analysis for Wind Resource









8.8 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	3500dinars	30
Lodging in Algiers for flight connection				Cash	8000dinars	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	648.1
			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 Euston Station	Using Oyster Card	10 pounds	16.1
			Train from London Euston Station to Lancaster station	Using Revolut Card	80 pounds	128.8
			Return train from Lancaster station to London Euston (off peak train)	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	iiffgaff mobile subscriptio	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			Cash		30
				Total Expenditure		3100.8
						3000