UNIVERSITY OF CAPE COAST

MODELLING THE IMPACT OF MODERN ENERGY SERVICES AND TECHNOLOGIES ADOPTION ON FINAL ENERGY DEMAND IN GHANA

ISAAC NDUR NYAME

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BY

ISAAC NDUR NYAME

Thesis submitted to the Institute for Oil and Gas Studies, College of Humanities and Legal Studies, University of Cape Coast, in partial fulfillment of the requirements for the award of Master of Philosophy degree in Petroleum and Energy Studies.

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DECLARATION

Candidate's Declaration

I affirm that this thesis is the product of my own independent effort and that none of its contents have been previously published or submitted for any other academic qualification, in of this institution or outside.

Signature………………………………………. Date……………………

Candidate's Name: Isaac Ndur Nyame

Supervisor's Declaration

I affirm that the preparation and presentation of this thesis were overseen in compliance with the University of Cape Coast's standards on thesis supervision.

Signature……………………………….. Date…………………………

Supervisor's Name: Prof. Edward Kweku Nunoo

ABSTRACT

The uneven distribution of fossil fuels and other energy resources, which most economies currently rely on, generates many questions as to whether the current energy transition targets can meet future energy demands. Despite Ghana's endowment in rich energy resources, the economy still encounters significant challenges in achieving universal access to sustainable, affordable, modern, and reliable energy services. There is no clear understanding regarding the potential impact of transitioning to modern energy services on final energy demand of Ghana. Using 2019 as the base year, the study modelled the effects of adopting modern energy services and technologies on final energy demand in Ghana. The study used cross-sectional data from 2019 and developed scenarios to forecast future energy demand of Ghana. The Model for Analysis of Energy Demand (MAED-2) was used to project the future final energy demand from 2019 to 2070. The findings indicated a high surge in total future final energy demand across all scenarios. The study revealed that while penetration of modern ES is more efficient, their adoption can lead to high overall energy consumption and energy per capita due to greater convenience and higher usage rates. The study recommends that energy efficiency technologies must be complemented with attitudinal change to prevent the rebound effect from efficiency measures.

KEY WORDS

Modern Energy Services

Final Energy Demand

Energy Consumption Patterns

Energy Transition

Economic Growth

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DEDICATION

To my family

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LIST OF ACRONYMS/ABBREVIATIONS

ACM	Agriculture, Construction and Mining
BaU	Business-as-Usual
COPs	Conference of Parties
EC	Energy Commission
ETM	Energy Transition Model
ES	Energy Services
GDP	Gross Domestic Product
GEF	Global Environmental Facility
GHG	Greenhouse Gas
GMSD	Ghana Meteorological Service Department
GNETF	Ghana National Energy Transition Framework
GWh	Gigawatt Hour
GWyr	Gigawatt Years
HEG	High Economic Growth
IEA	International Energy Agency
INDCs	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
Ktoe	Kilotonnes of Oil Equivalent
kWh	Kilowatt Hour
LPG	Liquefied Petroleum Gas
MAED	Model for Analysis of Energy Demand
MEG	Moderate Economic Growth
MMbbl	Million Barrels

NDPC	National Development Planning Commission
NREL	National Renewable Energy Laboratory
OCTP	Offshore Cape Three Point
RE	Renewable Energy
SD	Sustainable Development
SDGs	Sustainable Development Goals
SNEP	Strategic National Energy Plan
SOPCL	Saltpond Offshore Producing Company Limited
TAM	Technology Acceptance Model
TEN	Tweneboah-Enyenra-Entomme
TW	Terawatt
UN	United Nations
UNEP	United Nations Environment Programme
VRA	Volta River Authority

CHAPTER ONE

INTRODUCTION

Energy is a key component of modern life, significantly contributing to the promotion of a sustainable future. Governments, organisations, and institutions contend that without large-scale energy installations, no economy can effectively solve the difficulties of poverty reduction and development (Lawal, 2020). Energy serves as a starting point for accomplishing wider societal goals (Omorogbe, 2016). Furthermore, there is an undeniable correlation between population expansion and energy consumption. As a country's population increases, so does its demand for energy (Lawal, 2020). This makes it relevant to look at energy demand from a broader perspective. The Intergovernmental Panel on Climate Change (2019) highlights the connection between elevated GHG emissions and increased energy demand. The creation and treatment of primary energy, its conversion into secondary energy, and the ultimate use of energy for economic activity all contribute to the emissions of the energy industry. Typically, when petroleum products and biomass are used to produce electricity, processed heat, or steam, it results in the release of human-caused GHG emissions.

Background of the Study

Demand for energy increase as human society transforms from the traditional practices of hunting, gathering, and agriculture to the development of industrial and information-based organisations. Based on the United Nations projection for 2019, approximately 759 million inhabitants worldwide lack access to electrical power or electricity. Furthermore, the International Energy Agency (2021) estimated that 2.6 billion people continue to rely on "traditional" solid fuels such as dung, biomass, wood, kerosene, or charcoal for their daily energy needs such as heating, lighting, and cooking. Approximately 35% of the world's population lives in Sub-Saharan Africa and emerging Southeast Asia, mostly in rural regions and areas that are vulnerable to fragility and violence (IEA, 2021).

As stated in the work of Hesselman (2023), it is now too early to estimate the overall impacts of the COVID-19 pandemic on world energy accessibility. In November 2022, the IEA announced that the world population lacking access to electricity increased for the first time in twenty years, peaking around 775 million individuals. As mentioned by IEA in 2022, it is estimated that up to 10 million inhabitants living in Africa have been unable to pay for a basic set of energy services (ES) as a results of the pandemic. This involves the ability to use four light bulbs for several hours each day, a phone charger, and either a fan or a small television for a few hours each day.

Energy poverty, as defined by the World Bank (2020), implies a lack of access to or inability to purchase the necessary ESs for both material and social wellbeing. However, precisely determining the overall scope of this issue is challenging due to the absence of a universally accepted definition of energy poverty (Bouzarovksi & Petrova, 2015). A number of definitions of energy poverty now involve these key elements: (a) access to clean and safe fuels for cooking, lighting, or heating that are not in solid form; (b) access to a minimum amount of electricity for vital household appliances; (c) access to ES for social and productive purposes; (d) consideration of various factors that collectively define the 'quality' of access, including legality, reliability, affordability, quantity, sustainability, and safety (IEA, 2020). As noted by Bouzarovksi and

Petrova (2015), most definitions prioritise ‘access to ES’ over ‘access to energy supply’.

The term ‘energy services’ typically refers to the diverse advantages that individuals can get by transforming various energy sources into useful purposes (Bouzarovksi & Petrova, 2015). The relevant ES may include heating, cooking, lighting, refrigeration, cooling, or communication and information services. Different energy carriers such as wood, kerosene, electricity, or gas, obtained from different primary energy sources like solar, hydropower, wind, or petroleum, can fuel these services (Hesselman, 2023). For some specific people, what they ultimately require access to is “the energy service” rather than the source itself (IEA, 2020). It is crucial to focus on services rather than supply, as specific geographical or personal characteristics, along with energy efficiency rates, influence an individual’s energy requirements and actual consumption levels. From the IEA, 1,250 kWh of electricity per year is required to operate the expanded set of services when using standard appliances. However, using efficient appliances reduces the annual requirement to just 420 kWh. A household equipped with appliances that are not efficient will consequently need a greater amount of energy to achieve the same level of functionality (IEA, 2020).

Given the numerous difficulties presented by energy poverty on a worldwide scale, it is not surprising that governments and international organisations have started to solve the problem of ‘energy poverty’ in their own distinct manners (Hesselman, 2023). In 2015, the UN implemented 17 SD Goals with the aim of addressing significant issues in SD until 2030. SDG 7 requires all UN member states, including Ghana, to guarantee equitable access to affordable, dependable, and contemporary ES. The 'universal access target' in the SD Goals focuses primarily on achieving widespread power and clean cooking facilities for all individuals. However, it also explicitly includes considerations of affordability and reliability for all individuals, as well as the broader goal of sustainability (UN, 2017).

In Ghana, achieving SDG 7 is paramount to our economic development. Nevertheless, Ghana faces three primary energy problems: ensuring an adequate supply of energy to satisfy the growing demand, guaranteeing widespread access to ES, and decreasing the effect of energy on climate change (Asumadu-Sarkodie & Owusu, 2016; IPCC, 2020).

Based on available data, Ghana's population has grown from 24.7 million in 2010 to 30.8 million in 2021, with a corresponding total energy use of 5,537 ktoe in 2010 to 9,345 ktoe in 2021 (EC, 2022). Despite a decline in growth rate from 2.5% to 2.1%, projections indicate that the country's population will reach 50 million by 2050, leading to an increase in energy demand (EC, 2022).

The quest to overcome these energy challenges in Ghana, such as universal access to electricity and cultural or behavioural barriers to provide universal access to dependable, enduring, cost-effective, and contemporary energy for every individual, has caused the need for government policies aimed at promoting the utilisation of RE (Essandoh-Yeddu et al., 2017). These policies consist of, but are not limited to: the Renewable Energy Master Plan, the Ghana Integrated Power Sector Master Plan, the Gas Master Plan, Ghana's Updated Nationally Determined Contribution under the Paris Agreement (2020–2030), the Ghana Trade Policy, the National Infrastructure Plan by the National Development Planning Commission (NDPC), the Policy on Zero Gas Flaring, the National LPG Promotion Policy, the 2020 National Transport Policy, the LPG Recirculation Model, the National Energy Policy, the Energy Efficiency Regulations, and the Ghana Climate Change and Adaptation Plan.

The analysis of these policies and plans identified important gaps as well as opportunities for the development of the National Energy Transition Framework of Ghana (2020–2021). Establishing a hub for electric vehicle and battery technology development will enable Ghana to achieve its goal of significantly reducing global greenhouse gas emissions by concentrating on decarbonization, energy access and security, and energy efficiency. Ghana has developed net zero targets (energy transition pathways) for 2022–2070 that consider the use of nuclear power for electricity production, the implementation of carbon capture storage and utilisation technology, CNG, hydrogen and electric fuelled vehicles, sustainable aviation fuels, and energy-efficient end-use appliances.

The modelling analysis predicts a substantial increase in Ghana's total energy demand in the Energy Transition Model over the coming decades, primarily due to the country's increasing population growth. The forecast specifically predicts a surge in energy demand from its current level of 8,195 Ktoe to a significantly higher figure of 41,725 Ktoe by 2070.

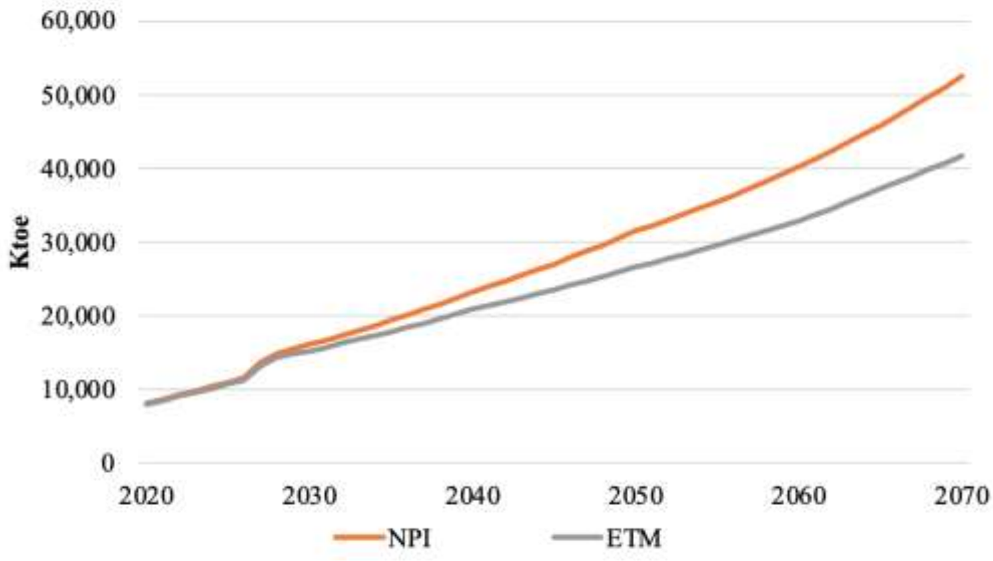

Figure 1: Energy Demand Forecast of Energy Transition Model and No Policy Intervention.

Source: (Ghana National Energy Transition Framework, 2022)

This necessitates proactive planning and strategic investments in energy infrastructure and resources to meet the evolving demands of Ghana's growing population and economy while also fighting climate change. Given Ghana's significant reliance on fossil fuels in its energy composition and its heavy dependency on energy imports, efforts to address climate change hold multifaceted importance.

In 2020, the total energy supply in Ghana was 491,379 TJ, of which 58 percent came from fossil fuels (IRENA, 2021), representing significant risks to energy security. To discover and examine various alternatives, it is critical to do a thorough analysis of energy consumption, taking into account the existing socio-economic growth patterns of the country (Agyekum, 2020). When addressing the issues related to climate change, we cannot ignore the significance of energy resources in meeting the needs of households, industries, transportation, and agriculture, among other sectors in any society. Various forms of energy sources are necessary to fulfil the need for light, cooking, and the production of electricity, among many other purposes. In Ghana, as in many other developing nations, the demand for energy surpasses the existing supply. Ghana's energy sector faces a significant obstacle in the form of the insufficient availability of modern energy services, including liquefied petroleum gas (LPG) and electricity.

However, there has been noticeable progress in this area over the past ten years. This has caused a high reliance on conventional energy sources, particularly biomass (mostly charcoal and wood fuel), to fulfil the energy requirements of households. Approximately 76% of households in Ghana rely on biomass for the purposes of heating and cooking water, according to estimates provided by Bawakyillenuo et al. (2021). Based on this, the study will conduct a thorough analysis that connects Ghana's individual sectors with future energy demand. This analysis will guide the development of energy policies aimed at achieving the goal of becoming an "energy-sufficient economy" to drive economic growth and development.

Statement of the Problem

The rising global energy demand and consumption, coupled with the unpredictable energy markets and production shocks encountered by many nations, have raised concerns over energy supply, management, security, and environmental implications (IEA, 2020). As countries strive to meet their growing demands for energy in the face of an energy transition agenda, understanding the implications of adopting modern energy services and technology becomes crucial. While the issue of energy transition, which includes the adoption of modern energy services, is a matter of great concern, there has been a controversy regarding the potential of renewable energies to meet the world's energy needs in a few decades without compromising economic growth (Dupont et al., 2021).

The answer to this question has been studied extensively, but no consensus has been reached (Ellabban et al., 2016; Jacobson, 2021). Rajbhandari and Nakarmi Shree (2017), on energy demand and scenario analysis of the Napal economy, revealed that the existing energy use trend would exert serious pressure not only on energy requirements but also on the national economy. In the case of Ghana, a study on renewal energy transition revealed that the country's energy sector and energy transition targets sit at the borderline of such a definition of energy policy failure (Sefa-Nyarko, 2024). Apart from this study, there limited studies on how this energy transition will affect the future energy demand of Ghana (Agyekum, 2020). Moreover, the National Energy Transition Framework of Ghana only projected the energy systems, failing to fully represent Ghana's current demand situation (Sefa-Nyarko, 2024). The urgency of these concerns is significant because of the unequal allocation of fossil fuels and other energy resources on which most countries currently rely. In the absence of knowledge regarding future energy demand of the economy, it becomes challenging to strategize energy supply in a manner that guarantees energy security, affordability, accessibility, and economic progress.

Despite Ghana's rich energy resources, the country still faces significant challenges in ensuring universal access to affordable, sustainable, reliable, and modern energy services. Based on the 2020 report on Ghana's energy by Energy Country Profile, only 22.2% of Ghanaians have access to clean fuels for cooking (Ritchie & Roser, 2021). This poses carbon emissions and energy security issues for Ghana, emphasizing the importance of energy self-sufficiency and related measures through government policies and cultural or institutional changes. Traditional energy sources, coupled with inefficient technologies, contribute to high energy poverty rates, environmental degradation, and hindered socio-economic development. The transition towards modern ES and technologies presents an opportunity to address these challenges. However, there is a lack of comprehensive understanding regarding the potential impact of adopting modern energy solutions on Ghana's final energy demand. This research aims to fill this gap by conducting a bottom-up analysis to forecast the implications of various pathways of energy transition on the country's energy landscape. By identifying potential future energy demand landscapes under different adoption scenarios, key drivers, barriers, and trade-offs associated with adopting modern ES and technologies, this study seeks to inform evidence-based policymaking and facilitate the transition towards a resilient and sustainable energy future in Ghana.

Purpose of the Study

The aim of the study is to analyse how the adoption of modern energy services and technologies influences the final energy demand in Ghana.

Specifically, the study seeks to:

1. compare the effect of different penetration scenarios on the final energy demand in Ghana from 2019 to 2070.
2. analyse the patterns of energy consumption per capita of Ghana under different penetration scenarios.
3. analyse the patterns of energy intensity under different penetration scenarios in Ghana.

Research Questions

To achieve the research objectives stated above, the study will answer the following research questions:

1. What is the effect of different penetration scenarios on the final energy demand in Ghana from 2019 to 2070?
2. How does the penetration of different adoption scenarios affect the final energy consumption per capita in Ghana?
3. How does the penetration of different adoption scenarios influence energy intensity patterns in Ghana?

Significance of the Study

This research will assist in examining the current National Determined Contributions and Ghana Net Zero Transition Pathways and Targets, with the goal of identifying drivers and barriers to sustainable transition and making policy reform recommendations in Ghana. This research will enhance the current knowledge base by offering valuable perspectives on the synergistic effects of government interventions and attitudinal changes on energy demand patterns. Businesses and investors can use the findings to identify opportunities and risks associated with investing in modern ES and technology, thereby supporting strategic decision-making in the energy sector. In addition, by analysing different adoption scenarios, the study will contribute to understanding the energy demand pathways towards sustainable energy transitions, helping to alleviate the effects of climate change and decrease reliance on fossil fuels. By examining the key drivers and barriers, the findings would offer valuable insights for policymakers, researchers, and practitioners working towards a more sustainable future to refine their strategies to ensure a more effective and culturally sensitive approach to sustainable energy transitions.

The Model for Analysis of Energy Demand (MAED) provides an alternative way to analyse energy sector development and forecast future energy demands. This is the first of its kind, with future energy demand determined by analysing medium- to long-term socio-economic, demographic, and technological development scenarios. Since the model adopts developing nations' characteristics in energy demand, it is the ideal model for developing nations. This will contribute to the overall pool of knowledge within the Ghanaian setting.

Again, the study will also determine feasible energy demand pathways for the nation to transition towards carbon neutrality within a reliable and efficient energy industry. The study aims to formulate medium- to long-term objectives and strategies for attaining a carbon-neutral economy. The aim of this work is to construct a bottom-up energy demand model for Ghana, with the base year being 2019.

Delimitation

The first delimitation of the study is that only data on the base year was collected on the various sectors of the economy. This explains why the study purposely gathered data in 2019. In addition, the study focused on the six economic sectors and the total energy demand for the four energy consumer sectors according to MAED model specifications.

Limitations

The secondary data that was collected from various sources may have been collected using different methodologies, and that may impact the accuracy of the data during analyses. Again, the nature of the study did not also permit the projections for future energy supply of the economy.

Organisation of the Study

The study was organised into five chapters. Chapter One gives a background to the study, states the problem at hand, spells out the objectives of the study, the purpose of the study, the significance of the study, the delimitations and limitations of the study, and how the study is organised. Chapter Two deals with the literature review of the study. In this chapter, the theories backing up the study and its objectives are explained, the empirical findings of the study are discussed, and finally, the conceptual framework of the study is elaborated. Chapter Three dealt with the research methodology. In this chapter, the research design and approach were explained, and sampling techniques were also discussed. Data collection procedures and related instruments were explained in this chapter as well. Data analysis, interpretation, and ethical considerations are also considered in this chapter. Chapter Four is about the presentation of findings, analysis, and discussion of results. Chapter Five presents the summary, conclusion, and recommendations of the study.

CHAPTER TWO

LITERATURE REVIEW

Introduction

This aspect aims to provide a comprehensive overview of the current academic knowledge on the subject under investigation. It will examine the available literature on ideas and concepts related to energy demand, modern ES, and technology. This activity's significance lies in its ability to provide context for this study by uncovering the discussions and past events that validate the necessity of conducting a scenario analysis on the effects of adopting modern ES on final energy demand. It will also help identify and address issues related to the energy transition agenda in developing countries, specifically Ghana. Additionally, the literature assessment will identify deficiencies in the existing material that require further investigation and resolution. Finally, it will offer instructions on Ghana's energy transition framework and its anticipated role in facilitating the economy's transition to a net-zero, sustainable state.

Theoretical Review

Technology Acceptance Model (TAM)

Researchers have proposed several theoretical models to study how the public adopts new technology. Davis introduced the highly utilised Technology Acceptance Model (TAM) in 1986. The objective of TAM is to forecast and analyse the behavioural dispositions of humans towards technology adoption (Davis, 1985). Fishbein and Azjen formulated the social psychology theory known as the Theory of Reasoned Action (TRA) in 1975, which forms the foundation of this model. The theory of reasoned action (TRA) suggests that beliefs play a crucial role in influencing attitudes, which subsequently influence motives and finally determine actions. Davis (1986, 1989) defined the categories used in the original TAM as perceived ease of use (PEOU), perceived usefulness (PU), and attitude and behavioural motive to use. Perceived ease of use (PEOU) and perceived usefulness (PU) are two factors that influence an end user's beliefs about a technology. These beliefs, in turn, determine the end-user's attitude towards the technology. Above all, the end-user's attitude towards the technology determines whether they will accept and use it. TAM categorises the aspects that influence an individual's attitudes towards adopting new technology into two contexts: perceived usefulness and perceived ease of use (Davis, 1986).

Perceived usefulness (PU) is a crucial factor in determining individuals' decisions to accept ES and technologies. Venkatesh (2000) argues that individuals' perception of the value of adopting new energy solutions will improve their energy experiences. Individuals can perceive that installing solar panels will lower their electricity bills, and utilising energy-efficient equipment will reduce energy usage and contribute to environmental sustainability. Once again, individuals believe that allocating resources towards RE technology, such as wind turbines, will not only reduce their dependence on fossil fuels but also yield enduring financial savings and ecological advantages (Venkatesh, 2000).

Gefen's (2000) study on perceived ease of use (PEOU) revealed individuals' belief that adopting ES will be effortless and convenient. That is, factors such as simplicity of installation, user-friendly interfaces, and availability of support services influence perceptions of ease of use. PEOU influences the adoption process by reducing barriers and resistance to adopting modern energy technologies (Ali et al., 2020). Individuals are more likely to overcome inertia and adopt technologies that they perceive as easy to use, potentially leading to changes in energy demand patterns. According to TAM principles, individuals are more likely to adopt smart ES and technologies if they perceive them as useful for reducing energy costs and enhancing comfort levels in their homes. For instance, in the household use of thermostats, if individuals perceive that thermostats are simple to install and operate, they are more likely to adopt them, leading to changes in cooling and heating energy demand within households. Graziano and Gillingham (2015) found that the ease of installation and operation of smart home energy management systems may influence consumers' decisions to adopt these technologies, leading to shifts in energy consumption patterns and demand profiles within households.

Research on the adoption of electric vehicles has shown that people's perceptions of the usefulness and ease of use of electric vehicles significantly influence their adoption decisions. Axsen et al. (2017), electric vehicles may be perceived as useful for reducing transportation costs, lowering GHG emissions, and promoting energy independence. Moreover, factors such as charging infrastructure availability, range anxiety, and vehicle affordability contribute to perceptions of ease of use and, consequently, adoption rates (Sierzchula et al., 2014). Thus, in the absence of these factors, consumers may refrain from accepting new technologies.

We must consider additional factors like financial costs, environmental awareness, and regulatory laws to thoroughly examine the country's receptiveness towards new energy technologies. Hence, by comprehending the opinions of governments, companies, and societies, we can efficiently tackle the obstacles and impediments that impede the diffusion of new technologies and encourage their broader acceptance and implementation (Yu et al., 2022). This methodology enables the integration of behavioural perspectives into the analysis of energy demand by enhancing the understanding of the process of switching to alternate energy sources.

Energy Efficiency

Energy efficiency has a deep historical root, with early civilisations developing methods to optimise energy use in various activities (Goldemberg, 2006). In the 18th and 19th centuries, the efficient use of coal and steam power became critical for driving economic growth and technological advancement. Innovations in energy-intensive industries spurred efforts to improve productivity and efficiency (Goldemberg, 2006) during the industrial revolution. Sorrel (2007) on behavioural economics highlights the role of human behaviour in energy consumption patterns, influencing individual and organisational choices related to energy use and efficiency. Effective energy management practices help identify opportunities for energy savings and optimisation within industrial, commercial, and residential settings (Sorrel, 2007). In recent decades, concerns about climate change, energy security, and resource depletion have intensified efforts to enhance energy efficiency globally (IEA, 2020). Initiatives such as the Paris Agreement and the SD Goals emphasise the importance of energy efficiency as a key strategy for attaining SD.

Energy efficiency is emerging as an important fuel in the global push to achieve sustainability goals. It is proving to be a key factor in addressing climate change, responsible for a substantial proportion (around 40%) of the projected decline in global CO_2 emissions by 2050 (IEA, 2020). Based on the submitted INDCs, most nations have already developed suitable energy efficiency programs to meet their national energy efficiency goals. However, meeting the emission reduction objectives and targets outlined in the Intended Nationally Determined Contributions (INDCs) is a crucial problem for all nations and the global community. Effectively controlling energy demand is a strong strategy for eliminating GHG emissions, particularly by introducing energy-efficient initiatives that decrease the quantity of energy required to ensure ongoing and sustainable economic development.

Nevertheless, the IEA noted in 2015 that the need to consider the "rebound effect'' phenomenon is a significant obstacle to creating effective energy efficiency programs. The benefits derived from technology elicit behavioural responses from economic agents, which may prevent the complete monetisation of energy conservation profits. The issue arises when energy efficiency programs, designed to reduce energy demand and GHG emissions, fail to achieve the anticipated outcomes due to the rebound effect in energy use. In the context of national and international efforts to address climate change, assessing the success of policies aimed at stimulating energy efficiency improvements is critical. This assessment takes into account the magnitude of the potential rebound impact. Therefore, policymakers must thoroughly evaluate and consider any possible rebound effects when designing energy efficiency measures to ensure that they set realistic goals.

The energy efficiency paradox

The energy efficiency paradox, a concept deeply intertwined with the broader landscape of energy economics and policy, challenges the traditional assumption that improvements in energy efficiency inevitably led to reduced energy consumption and environmental benefits. This concept has roots dating back to the early 20th century (Brookes, 2000). Initial economists and policymakers (Howarth & Andersson, 1993; Sanstad & Howarth, 1994) believed that improvements in energy efficiency would naturally lead to decreased energy consumption. However, empirical evidence began to emerge, suggesting that this relationship was not straightforward (Herring, 1999). The energy efficiency paradox poses a dilemma for policymakers seeking to promote energy efficiency as a means of reducing energy demand and mitigating climate change.

While energy efficiency measures are widely recognised as cost-effective and environmentally beneficial, their potential to stimulate additional energy consumption complicates policy decision-making (Gillingham et al., 2013). Therefore, policymakers may jeopardize the success of energy efficiency policies by overlooking a set of mechanisms known as 'rebound effects', which can reduce the potential energy savings from energy efficiency improvements (Kipouros, 2017). This is because the advantages of these technologies elicit behavioural reactions from economic actors (such as households and firms), which can prevent the complete realisation of the financial gains from energy savings.

Rebound effect

In his influential paper, sometimes referred to as the 'Jevons Paradox', Jevons (1865) was the first economist to introduce the concept of the rebound effect. However, Brookes (1979) and Khazzoom (1980) brought attention to the contradictory connection between improved energy efficiency and the subsequent rise in demand for ES, leading to widespread discussion of the rebound effect (RE). This led to a resurgence of controversy, and the rebound effect (RE) became a prominent topic in the field of energy economics. Saunders (1992) named this relationship the ‘Khazzoom-Brookes Postulate’ and links RE analysis to neoclassical theory. He proposes that energy efficiency enhancements may increase rather than reduce energy demand, emphasizing two primary avenues: (i) by efficiently reducing energy costs, and (ii) by stimulating economic growth. In the first scenario, economic actors will modify their energy requirements in response to price changes, whereas in the second scenario, economic expansion will necessarily lead to an increased need for energy.

While the literature does not provide a precise description of the rebound effect, it is widely acknowledged that several factors might diminish the potential energy savings resulting from enhancements in energy efficiency. Greening et al. (2000) as well as Sorrell and Dimitropoulos (2008) categorise these mechanisms into three types: direct effects, indirect effects, and economy-wide effects. Direct rebound effects pertain to distinct ES, including heating, cooling, lighting, and motion. Improving energy efficiency will reduce the extra expenses associated with energy provision, leading to a reduction in the service’s implied price, thereby increasing demand for that specific service (Greening et al., 2000). Enhancements in energy efficiency have a direct influence on energy usage, but they can also have an indirect impact through other pathways. Indirect rebound effects manifest in many forms and impact energy use at different points in time.

(Sorrel, 2007) revealed that indirect rebound occurs when efficiency gains result in broader economic benefits, such as lower production costs or increased economic activity, leading to higher overall energy consumption within the economy. But the sum of the direct and indirect rebound effects results in an economy-wide rebound effect.

The economy-wide rebound effect refers to the net impact of various interrelated changes that are separately complex, resulting from an increase in energy efficiency. This increase leads to both an expansion in firms' production possibilities and an increase in consumers' real disposable income. The cumulative impact of these changes made by consumers and enterprises can have a substantial effect on the whole economy (Greening et al., 2000). Nevertheless, Sorrell and Dimitropoulos (2008) argue that empirical proof regarding the RE is unclear and lacks a definitive conclusion. They emphasize that several authors in the literature have employed various definitions of RE. The absence of uniformity in defining the rebound impact, its origins, and their interconnection, coupled with the absence of a standardised method for quantifying it, presents a formidable challenge in estimating the economy-wide rebound effect.

The current empirical literature is characterised by a lack of clarity and consistency. Haas and Biermayr (2000) assess the extent of the rebound impact on domestic space heating in Austria by employing time-series and cross-section analysis from 1970 to 1995. The study findings indicate a rebound effect ranging from 20% to 30%, demonstrating that enhancements in energy efficiency result in energy conservation and subsequently contribute to a decrease in CO_2 emissions. Nevertheless, the realized savings are lower than the savings estimated by engineering calculations because of the rebound effect.

Thus, the energy efficiency paradox has significant implications for energy policy and sustainability efforts. As stated by Sorrell (2007), energy efficiency alone may not be sufficient to achieve meaningful reductions in energy consumption and environmental impacts. Instead, policymakers must consider a range of factors, including behavioural responses, market dynamics, and technological innovation, when designing effective energy efficiency policies and strategies.

Empirical Review

This section discusses previous related empirical findings with the aim of highlighting and providing a more suitable context to situate this current study as well as relate findings to the study area. In recent times, the adoption of modern energy services among predominantly developing nations has been one of the most studied areas in energy demand and supply analysis (Yang et al., 2021). These studies primarily focus on the implications of various adoption scenarios, uncertainties, and sensitive issues related to technological advancement and energy penetration, and their impact on the final energy demand.

Sefa-Nyarko (2024) discusses Ghana's National Energy Transition Framework. Domestic ambitions and scepticism in global affairs confuse the concepts of 'justice and fairness'. The study utilizes a recently developed worldwide framework for energy justice, which aims to ensure equitable allocation of decision-making power, representation, and the costs and benefits associated with ES over different periods and geographical locations. The study applies this model to examine Ghana's National Energy Transition (NET) framework. The report aims to analyse the government's rationales for not giving priority to green energy and for making modest progress towards the net zero emission goal by 2070.

Domestic considerations such as affordability and accessibility primarily influence Ghana's framework for energy justice, but the study also reveals the presence of several other elements. The researcher used thematic analysis on four main sources of data: interviews, news articles, Living Standards Surveys, and policy documents. They found that the discussions on energy transition were not fair because of the complicated interactions between economic factors, global politics, and unresolved national and historical grievances. This also obscured the evident discrepancy between energy service policies and their implementation. The study found that the government's current approach is insufficient to meet the national energy transition goals. However, if western countries and major emitters can demonstrate sincerity and fairness in their policies and actions regarding climate action and energy transitions, there is potential for change.

Battulga and Dhakal (2023) conducted a study on energy demand modelling for the transition from a coal-dependent metropolis to a low-carbon city. The study focused on long-term energy demand forecasts for Ulaanbaatar until 2050, using the Model for Analysis of Energy Demand (MAED). This study aimed to identify and assess the potential ultimate energy consumption of a city that heavily relies on coal, with the goal of transforming it into a low-carbon city. Four scenarios were constructed by including the current local and national policies in the socio-economic and energy sectors, together with more ambitious policy and technology measures suggested by many studies in the MAED-D model. The study findings indicate that widespread adoption of electricity and RE, implementation of energy efficiency measures, and reduction of energy intensity across all sectors can effectively decrease future energy demand and facilitate the transition towards a low-carbon metropolis.

Aboagye (2017) investigated the policy implications of Ghana's correlation between energy consumption, energy intensity, and economic growth. The study noted that the oil price shocks in 1939/74 and 1979/1980, along with the unreliable supply of oil compared to the growing demand for energy-based resources, strengthened the significant impact that energy may have on economic development. Advocates often promote reducing energy intensity as a means to efficiently use energy resources and minimize the negative impact of energy shortages on economic development. Based on the annual time series data set from 1981 to 2014, the study discovered compelling evidence of a valid long-term connection between energy consumption and economic growth, as well as energy intensity and economic growth.

Different adoption scenarios have substantial impact on the ultimate energy demand in various sectors, which in turn affects energy efficiency, emissions, and the specific patterns of energy consumption in each sector. With that, Emodi and Dioha (2019) conducted a study on the effects of different energy access scenarios on Nigerian households by 2030. They found that achieving complete access to modern energy by 2030 would result in a significant decrease in final energy demand, specifically around 845 PJ. This reduction corresponds to a 52.4% decrease compared to the baseline scenario. The study also found that implementing a fully modern access system would lead to a substantial decrease in local air pollutants. However, it would also result in a significant increase in CO_2 emissions, namely 16.7 $MtCO_2$, compared to the baseline scenario. Projections indicate that urbanisation and household development in Nigeria will lead to a 92.3% increase in home energy demand by 2030. Therefore, by implementing advanced technologies like the progressive energy scenario, the rise in energy consumption can be reduced using efficient cooking and lighting equipment.

Brockway et al. (2021) emphasised that most global energy scenarios predict a significant change in the connection between energy consumption and gross domestic product (GDP). Many scenarios suggest absolute decoupling, where energy usage decreases but GDP continues to increase. However, there are only a few instances of complete decoupling, and the current global patterns are moving in the opposite direction. This study examines a potential reason for the historical correlation between energy consumption and GDP, which is that the overall rebound effects resulting from enhanced energy efficiency are greater than what is typically believed. The study analyse the available information about the magnitude of economy-wide rebound effects and investigate the extent to which these effects are taken into account in the models utilised to generate global energy futures. Although the evidence base is expanding and of high quality, it notably varies in terms of the applied methodology, assumptions made, and rebound mechanisms considered. There is a wide range of variations, the outcomes are generally aligned and indicate that rebound effects at the national level could diminish over 50% of the anticipated energy savings resulting from enhanced energy efficiency. Furthermore, integrated assessment and global energy models often fail to consider numerous pathways that contribute to rebound effects. Thus, we deduce that global energy projections might underestimate the future pace of global energy demand expansion.

Akom et al. (2020) authored a study on the energy framework and policy direction guidelines for Ghana, focussing on the period from 2017 to 2050, with the aim of developing energy plans for the country. Their research endeavours to create an integrated energy planning (IEP) framework for Ghana that serves as a blueprint for tackling energy obstacles, advancing energy efficiency in both demand and transmission, decreasing CO2 emissions, and harnessing renewable energy sources (RES). The report proposes the use of non-conventional RE resources, which account for 40% of the country's energy mix. It also advocates promoting energy efficiency in both demand and transmission, as well as integrating RE sources to reduce CO2 emissions by approximately 40%.

Also, there has been a noticeable decoupling between economic growth and energy consumption in several countries. Despite its potential benefits, this fact poses concerns for energy systems modellers. The process of making assumptions, particularly about the connection between socio-economic forces and energy demand, can no longer be based on simple connections. Consequently, García-Gusano et al. (2018) proposes a dual evaluation method to address that issue. The study proposes using econometric models as effective instruments for forecasting electricity demand in Spain. The study recommends the integration of these precise energy demand estimates into the LEAP framework-developed Spanish energy system model. The findings indicate significant disparities (reaching up to 18% by 2050) in the necessary power generation, which to a certain degree; include alterations in the composition of energy production technologies. In addition, when considering power demand, the utilisation of accurate demand forecasts greatly affects the conduct of different sectors. This illustrates that a basic set of estimates overestimates industry need while underestimating residential demand. To summarise, energy systems modellers should refrain from making oversimplified assumptions when incorporating exogenous demand estimates, as the decoupling effect can significantly affect the accuracy of their models.

Karakara and Osabuhien (2021) conducted a study to determine the factors that influence the amount of fuel households use for domestic purposes. They specifically focused on two types of fuel: 'clean' fuels and 'dirty' fuels. The study utilised data from the Demographic and Health Survey, which consisted of a sample of 11,835 households located throughout Ghana. The study employed binary categorical models, namely binary logistic and binary probit models, to examine the factors influencing a household's choice between 'clean fuel' and 'dirty fuel'. These models utilised socio-economic characteristics and spatial disparity (regional location) to estimate the likelihood of using either type of fuel. The findings indicate that socio-economic factors have an impact on households' energy consumption, and rural households are at a disadvantage compared to urban households when it comes to embracing clean fuels. Furthermore, households led by men are more likely to embrace clean fuels than households led by women. As households become wealthier, they tend to prefer clean fuels for lighting over cooking. Nevertheless, the majority of households still rely on solid fuels, such as charcoal and firewood, as their primary source of fuel for cooking. The use of these contaminated fuels may impede households' well-being due to indoor pollution. The study suggests that policymakers should focus on providing homes with clean and improved energy sources.

Gillingham et al. (2016) elucidated the concept of the rebound effect and furnished a comprehensive manual for economists and policymakers who are keen on understanding its presence and extent. Studies in the literature examine the rebound effect resulting from a free external increase in energy efficiency, while others concentrate on the effects of specific energy efficiency strategies. This distinction has significant consequences for welfare and policy outcomes. They provided the most dependable evidence currently accessible about the magnitude of the energy efficiency rebound impact and examined scenarios in which estimating it is quite challenging. Considering this perspective, the study introduced a novel approach to conceptualising the macroeconomic rebound impact. In summary, the current study offers limited evidence to support the backfire concept. Nevertheless, our comprehension of the macroeconomic rebound impact is still restricted, specifically with regard to spurred innovation and productivity development.

Occasionally, the process of adapting to climate change may require energy consumption, which can undermine efforts to reduce GHG release. There are many examples, such as air conditioning or water desalination. Ben-Ari et al. (2021) demonstrated that adaptation responses to climate change can have varying effects on energy demand. They emphasise the importance of understanding these effects in order to minimise adaptation’s impact on energy demand and prevent maladaptation. Therefore, the adoption of various strategies to cope with climate change, such as the promotion of air conditioning or the increase of vegetation, might result in significantly divergent energy consumption outcomes (Ben-Ari et al., 2021).

Davis et al. (2019) introduced a framework for creating a scientific tool using the long-range energy alternative planning (LEAP) system. Davis et al. (2019) designed this tool to assess energy usage and provide strategies for reducing GHG emissions in a country's energy system. The established framework is utilised to construct a technology-explicit, data-dense energy model for Canada. This model has over 2 million data pointed and integrates 13 regions, making it applicable to one of the most energy and emission-intensive nations in the world. The model's accuracy was verified using historical data, which showed that emissions varied between 0 and 1.2%. This confirms that the framework can provide precise evaluations. The model was utilised to produce fundamental Canadian energy-emissions projections up to 2050, which are currently absent in existing literature. The created framework offers powerful functionalities that are beneficial for analysing energy efficiency, planning energy usage, and assessing GHG mitigation.

Mensah et al. (2021) conducted a study that examines the role of bioenergy in balancing the power grid of a 100% renewable power sector in Sub-Saharan Africa, with a focus on addressing the issue of energy poverty in the region. Ghana is the case nation used in this investigation. Two methodologies are utilised: the bioenergy estimating method is used to determine Ghana's technical bioenergy potential, while the LUT model is applied for power sector transition modelling. The Ghanaian bioenergy potential of 48.3 TWh is utilised in the electricity sector through the LUT model to create six different scenarios. These scenarios focus on the significance of bioenergy, the costs associated with GHG emissions, and policies aimed at mitigating climate change. From the Best Policy Scenario, an electrical efficiency of 37.2% could provide 18 TWh of electricity from bioenergy for grid balancing. This amount would account for 16.9% of Ghana's electricity demand by 2050. The levelized cost of electricity decreases from 48.7 €/MW in 2015 to a range of 36.9–46.6 €/MWh in 2050. In the current policy scenario, the cost of electricity rises to 76.4 €/MWh without factoring in the expenses associated with GHG emissions. The findings demonstrate the feasibility of an affordable and environmentally balanced RE system for the sub-Saharan African region.

Arndt, Asante, and Thurlow (2015) noted that Ghana's long-term economic development is at risk from human-caused climate change due to its reliance on rain-fed agriculture, hydropower, and unpaved rural roads. Arndt, Asante, and Thurlow (2015) utilised the CGE model to assess the overall effects of climate change in Ghana's economy. Their study discovered that climate change has a detrimental impact on the country's welfare, particularly affecting impoverished and urban households, as well as the Northern Savannah Zone. Furthermore, they verified that there is significant diversity among different scenarios regarding the magnitude of climate effects and the relative importance of impact channels within sectors. This highlights the necessity of employing multi-sector strategies that consider the uncertainty of climatic conditions.

Zhang et al. (2022) conducted a study that explores two potential pathways to accelerate technological advancement: technology adoption and technical breakthroughs. Foreign direct investment (FDI) can potentially improve the host country's ability to innovate independently, reduce the risk associated with independent innovation, and decrease costs. To achieve this objective, a two-stage analysis was carried out at the industrial level in Guangdong, China, covering the period from 2000 to 2018.

In the first stage, the study estimated the total factor energy efficiency (TFEE) scores using the super-efficiency data envelopment analysis (DEA) methodology. In the second stage, the study examined how technological innovation and foreign direct investment (FDI) are affecting energy efficiency. This was done by using system GMM regression on the entire sample of the manufacturing sector, as well as a sub-sample based on research and development (R&D) intensity. The findings suggest that energy consumption in most manufacturing sectors is effective, and the involvement of foreign direct investment (FDI) leads to beneficial effects on energy efficiency through the transmission of knowledge and resources. Another study that looks at the relationship between foreign direct investment (FDI) and technical innovation shows that copycat innovation depends on companies that get money from foreign investors using transfer technology strategies to make energy use more efficient. This study’s findings have significant implications for energy usage policies and the promotion of sustainable economic growth.

Poblete-Cazenave and Pachauri (2021) suggested that countries with a significant proportion of their population experiencing energy poverty are likely to witness an increase in both appliance usage and power demand. Methods for estimating the latent demand of energy-poor communities frequently assume a consistent income elasticity of demand. The study proposed a new method for estimating the relationship between electricity demand and income. Their methodology employs simulation techniques and takes into account nonlinearities and other significant factors. The study used microdata from four developing nations to evaluate the consequences of policy scenarios in achieving SD Goal SDG 7 within various socio-economic futures. The analysis indicates that the implementation of policies for universal power access leads to a greater overall demand for energy. However, the average electricity consumption per person is lower compared to scenarios without access rules.

Additionally, the study observed substantial disparities in the adoption rates of electrical appliances across different countries, types of appliances, climates, and income levels. Notably, all four countries and socioeconomic scenarios show a consistently high proportion of power used for entertainment purposes. Nevertheless, the proportion of energy consumed for food preservation and preparation, as well as garment upkeep, increases substantially as individuals' income grows, enabling them to purchase equipment that offers more convenience. The findings of the study validate that when energy-deprived communities are provided with electrical services, their demand increases. However, failing to include the variations in the population can lead to inaccurate estimations.

Smith et al. (2019) found that Sub-Saharan Africa rarely views the charcoal sector as a tool for promoting rural development or reducing poverty. Instead, existing laws frequently exclude rural producers. These stakeholders' low comprehension hinders the progress of establishing a sustainable sector that avoids exacerbating rural marginalisation. The study evaluates the diversity of rural producers in Mozambique, who serve two urban charcoal marketplaces of varying sizes. Based on data collected from 767 household surveys, the research indicates that the size of the urban market affects rural producers' characteristics and the scale at which they operate. The producers serving the larger urban market had a higher level of dependence on charcoal for generating money. In particular, small-scale producers relied heavily on charcoal income, which accounted for over 95% of their family incomes. Producers catering to the smaller market, on the other hand, had a wider range of sources of revenue, making them less reliant on earnings from charcoal. Typically, larger-scale producers had more wealth, higher absolute incomes, and relied less on charcoal income.

Further research suggests that not only the most impoverished individuals were involved in rural charcoal production. The presence of producers stuck in small-scale production may be a result of larger metropolitan markets, rather than an inherent aspect of the industry. The projected expansion of smaller urban areas and the subsequent increase in demand for charcoal will create significant prospects for generating income in rural regions. This is expected to result in changes in the composition of producers and the scale of production. Instead of adopting current formal methods that exclude rural stakeholders, tiny urban areas provide the opportunity to create fair production systems that can promote sustainable energy and rural development.

In their study on projected energy demand in UK household heating, Baruah and Eyre (2015) observed that fossil fuels are the primary source of space heating in the UK. Consequently, addressing climate change requires a fundamental transformation in space heating systems. They view the problem as challenging because of the inefficient building stock and high natural gas usage. As a result, they published updated, quantified projections of home energy consumption in the UK up to 2050. According to their research, the UK will continue to rely on gas for heating unless there is significant legislative intervention. This would contradict the purpose of reducing carbon emissions. Currently, UK policymakers prefer an alternate system that mainly relies on heat pumps driven by low carbon electricity. According to their research, they determined that a certain change in this direction is probably necessary, but depending entirely on this approach presents many issues.

Spiecker and Weber (2014) conducted a scenario study on the future of the European power system and the effects of variable RE. They noted that the changing European energy system presents new issues. As a result, electricity production from unpredictable sources such as wind and solar energy has increased significantly. However, their study has not provided clear guidance on how to achieve future emissions reduction goals or what the future power system will entail. Significant levels of uncertainty specifically influence both the long-term investments in power plants and the short-term operation of these plants.

Abban and Awopone (2021) conducted a techno-economic and environmental analysis of energy scenarios in Ghana. Their study examines the trends in the power grid's energy potential over the past ten years and assesses the impact on the power grid's direction. Additionally, the study evaluates the economic viability and sustainability of RE sources in Ghana. The study utilised the Long-range Energy Alternatives Planning System (LEAP) technology to analyse three distinct scenarios: energy demand, cost-benefit, and carbon limitation. Once again, they designated 2018 as the starting point and 2048 as the concluding point. Over the next three decades, the analysis found that implementing a RE technology-based generation system in the country will lead to significant benefits, including a sustainable and safe environment as well as reduced carbon emissions, provided that the government has the financial means to support such development.

According to the available literature, there is currently no agreement on whether renewable energies can fully meet our energy requirements in the near future. Dupon, Germain, and Jeanmart (2021) have provided fresh insights into the viability and economic consequences of the energy transition by creating a methodology that combines a macroeconomic model with two sectors (energy and non-energy) and an energy model capable of determining the maximum capacities of solar and wind energy. The analysis found that achieving a full global energy transition within the current business-as-usual framework is not possible by the end of the century.

Their rationale stems from the escalating capital requirements of the energy industry, which impede economic expansion and the shift towards sustainable energy sources. They assert that we can achieve a full transition by 2070 if we maintain the current level of energy demand, sustain capital growth above historical levels, and make significant advancements in energy efficiency. The proposal suggests that this technique necessitates a substantial increase in the savings rate, resulting in a detrimental effect on consumption and ultimately leading to stagnation at the end of the transition.

Fujii et al. (2019) conducted a study on energy demand modelling in emerging economies, namely in Bangladesh, using MAED-2 with sectoral decomposition. The study found that within a span of ten years, both the overall power generation capacity and the amount of electricity generated per person have nearly doubled. According to the study, it is crucial to have projections of sectoral demand growth for both the short and long term in order to fulfil the increasing demand and stay in line with the development trend.

Khalid et al. (2021) found that several factors, including self-efficacy, environmental concern, awareness of RE, and beliefs about its benefits, strongly and positively influence consumers' willingness to adopt RE. The study revealed that the cost of RE had a negligible impact on customers' willingness to accept RE, and the perception of risk/trust had a similarly insignificant effect on consumers' adoption of green energy. Bilgili and Ozturk (2015) found that there is a positive relationship between the long-term dynamics of biomass energy consumption and GDP growth. They also discovered a favourable correlation between RE and economic growth.

Sorrel, Gatersleben, and Druckman (2020) emphasize that 'Energy sufficiency' entails decreasing the use of ES in order to avoid the resulting environmental effects. Taking specific steps like reducing car trips or reducing working hours, income, and overall consumption (known as 'downshifting') can achieve this. However, neither approach may have as many environmental benefits as expected. Firstly, individuals can accumulate funds towards alternative goods and services that require energy use, thereby creating a rebound effect. Furthermore, individuals may feel that they have fulfilled their environmental responsibility and allocate their time and financial resources towards more energy-intensive products and activities, resulting in spillover effects.

Additionally, by conserving time, individuals can allocate it to alternative activities that require effort and involvement, a phenomenon known as time-use rebounds. This research examines the existing knowledge regarding rebounds and spillovers resulting from sufficiency acts, as well as time-use rebounds resulting from downshifting. The study finds that rebound effects can significantly diminish the expected energy and emission savings resulting from sufficiency actions. Additionally, it suggests that these actions have a minimal impact on overall energy use and emissions. Furthermore, it indicates that downshifting working hours and income can lead to a decrease in energy use and emissions, although the reduction may not be proportional.

The long-term prediction of energy supply and demand is crucial in Africa due to the continuous rise in energy needs, limited availability of resources, heavy reliance on fossil fuels to meet these needs, and global concerns regarding energy-related environmental problems. Ouedraogo (2017) utilised the Long-range Energy Alternative Planning System (LEAP) to examine and forecast energy demand and associated emissions for Africa from 2010 to 2040. The study specifically investigated various scenarios and their potential impact on SD strategies. The report projects a three-fold increase in energy consumption in 2040 compared to 2015, leading to a corresponding rise in GHG emissions. The researcher stated that this would put more strain on local and regional energy resources, as well as carbon reduction systems, highlighting the importance of energy conservation and reducing GHG emissions. The analysis also found that implementing the energy efficiency program will result in a 1% reduction in oil and coal contributions to global energy consumption, while the proportion of renewables will increase by the same percentage.

Ahenkan et al. (2021) examined the characteristics, prospects, and obstacles of the solar energy sector in Accra. This study employed a qualitative research methodology to examine the progress of the solar energy market in

Accra. They conducted an analysis of the Ghanaian government's policy framework for achieving sustainable energy in the country, as well as the emerging opportunities and obstacles related to the growth of this specific energy sub-sector in Accra. The study revealed that insufficient financial backing from institutions and service providers, a lack of post-purchase technical assistance, limited availability of consumer credit options, a lack of public education, and low awareness among the public about solar energy technology are significant obstacles to the progress of solar energy in Accra. Furthermore, the lack of harmony in the net metering policy poses a significant obstacle to the adoption of solar energy and the growth of the city's market.

Awopone (2017) conducted a study on Ghana's energy systems with the aim of improving their efficiency and effectiveness in the long run. The study focused on assessing several options for energy solutions in Ghana from 2010 to 2040. Four scenarios were constructed using the Long-range Energy Alternating Pathways (LEAP) methodology, which is based on the primary impacting elements identified in the literature. The scenarios include the base case, which relies on coal as its primary energy source; the modest RE technology scenario; and the high RE technology scenario. The policy restrictions examined encompassed emission objectives, carbon levies, enhancements in transmission and distribution losses, and increases in demand-side efficiency. The study found that effective policies for sustainable electricity generation have a crucial impact on reducing CO2 emissions in Ghana. Furthermore, the implementation of carbon minimisation laws will encourage the diversification of the generation mix by increasing the use of RE technology. The analysis suggests that the most effective energy plan for Ghana would involve enhancing energy efficiency, reducing transmission and distribution losses, and maximising the use of RE sources.

Given the depletion of existing energy generation, the study aimed to investigate the notable lack of energy efficiency and conservation practices among Ghanaian consumers. Based on the growing population and their increasing demands (Botwe-Ohenewaa et al., 2022), research has been conducted on household energy consumption in Ghana. The study found that implementing energy efficiency and conservation measures resulted in a substantial 5.14% reduction in energy consumption. This reduction had considerable economic and environmental benefits. As a result, the study suggested the need for policies and tactics to facilitate widespread education, ensure the execution of energy efficiency and conservation initiatives, and promote the use of energy-efficient equipment.

Lessons learned and gaps from related studies

The literature study revealed that scholars have extensively explored many aspects of energy adoption, efficiency, and sustainability in numerous sectors and geographies. The author emphasize the importance of adoption scenarios in determining final energy demand. Various studies have shown that modern energy access can lead to significant reductions in energy demand, but there is also a possibility of increased CO2 emissions. These studies include those by Spiecker & Weber (2014), Baruah & Eyre (2015), Arndt, Asante & Thurlow (2015), and Dupon, Germain & Jeanmart (2021). Climate change adaptation is essential, but it presents numerous obstacles due to the potential for diverse consequences on energy demand resulting from different responses.

Therefore, careful attention is necessary to prevent maladaptation. The National Energy Transition Framework and the Gas Master Planner are policy frameworks that prioritise integrated energy planning to tackle difficulties, improve efficiency, and encourage the use of renewable energy sources. Nevertheless, there is a significant absence of agreement regarding the practicality of a full energy transition and the efficacy of renewable energies in satisfying future energy needs (Abban & Awopone, 2021; Spiecker & Weber, 2014; Dupon, Germain & Jeanmart, 2021; Emodi & Dioha, 2019; Sefa-Nyarko, 2024).

Existing literature (Malla, 2013; Fufii, Komiyama, & Sieed, 2019; Battulga & Dhakal, 2023) indicates the numerous studies conducted on long-term energy demand forecasts worldwide. Nevertheless, there is a scarcity of research on extended energy demand forecasts for Ghana. Awopone (2017) and Akom et al. (2020) developed an integrated energy planning framework for Ghana as a set of instructions for addressing energy challenges through long-term energy alternative planning (LEAP). Although LEAP permits sectoral analysis, its framework is more universal, intended to be adaptable to many situations, and does not fully depict the specific circumstances of developing countries (Banerjee et al., 2016).

The literature suggests the necessity of a more comprehensive methodology tailored to the circumstances of developing countries. This methodology should enable the modelling of the effects of specific factors on energy demand, such as GDP growth, technological progress, lifestyle changes, and policy influences. In 2006, the energy commission of Ghana developed the Strategic National Energy Strategy (SNEP), which is the country's first long-term energy strategy. Ghana's ongoing issues with electricity supply prompted the creation of the plan, which spans from 2006 to 2020 (Essandoh-Yeddu, 2017). In 2022, the creation of the National Energy Transition Framework (2022–2070) facilitated the country's transition towards achieving net-zero emission targets.

Forecasting energy demand, understanding consumer behaviour towards RE, and long-term energy planning for SD remain focal points. Notably, there are still gaps in the integration of socio-economic factors, technology adoption, lifestyle changes, and policy implications, as well as in understanding the impacts across different sectors in energy demand estimates. Hence, it is imperative to examine these discrepancies in order to guide evidence-driven policies and initiatives that aim to accomplish a sustainable energy transition.

Conceptual Review

The Concept of Energy Demand

The concept of energy demand is fundamental to understanding the patterns, drivers, and implications of energy consumption within societies. As stated by the IIEA (2021), energy demand focusses on the quantity of energy required by individuals, households, industries, and economies to satisfy various needs, such as heating, cooling, transportation, industrial processes, and electricity generation. Meeting energy consumption needs, increasing concerns about energy cost instability, and the global focus on reducing CO2 emissions have brought significant attention to the urgency of taking action to provide energy security, combat climate change, and maintain economic stability.

This need is now more prominent than ever, and it applies to both industrialised and developing nations. The Paris Agreement, the inaugural globally enforceable climate accord, resulted from over twenty years of arduous international deliberations on addressing climate change. Nevertheless, despite the combined efforts, worldwide energy-related carbon dioxide emissions have surged by over 50% since 1992, primarily driven by economic expansion and the escalating use of fossil fuels in developing nations (IEA, 2016).

Energy consumption in emerging nations has increased by nearly three times in the previous thirty years, and the IEA predicts that this trend will continue to rise quickly in the next few years. Several emerging nations have shifted from an agricultural to a more energy-intensive stage of industrial development, resulting in an increased demand for modern goods and services that require a significant amount of energy. In addition, the IEA (2014) asserts that population growth and the increasing rate of urbanisation have intensified the growing need for energy, particularly in developing nations.

The UNIDO (2010) emphasises that access to clean, dependable, and affordable energy is crucial for a country's prosperity. Failure to meet the increasing demand could jeopardise SD. We can disaggregate energy demand into various sectors, each with unique characteristics and drivers. These sectors typically include residential, commercial, industrial, transportation, and agriculture, each of which accounts for a distinct share of total energy consumption (Davis et al., 2010). In order to understand consumption patterns and enable target interventions to improve energy efficiency and sustainability, there is a need for energy demand analysis at the sectoral level.

Drivers of energy demand

Gross domestic product per capita (GDP/cap), a measure of economic development, and the current energy price typically influence the demand for energy (Chateau, 2022). Climate, natural resource availability, and geography account for variations in energy consumption per capita among nations with similar GDP per capita and energy prices, as well as disparities in the relationship between energy demand and GDP. Energy demand arises from the satisfaction of energy requirements within a specific energy price framework. However, energy is not required for its own sake, but rather for the purposes of the services it enables. Different energy quantities are required to perform the same service, depending on the equipment employed. For instance, moving over one kilometre with a bicycle or an automobile necessitates different amounts of energy.

Hence, due to technological advancements, the dynamics of the need for ES may differ from that of the energy demand (Chateau, 2022). We can classify the drivers of energy demand into two primary categories. First, the socio-economic drivers represent the demands for ES. Secondly, technological drivers play a role in converting these needs into actual energy demand (Labandeira et al., 2017). This pertains to energy end-users, including industries, buildings, transportation methods, agriculture, and standardized energy products produced and delivered by the energy industry (such as refineries and power plants). In support of the findings by Labandeira et al. (2017), the IEA (2020) states that the primary factors influencing energy demand are demographic, technological, and economic factors, together with government policies and programs. Demographic considerations, such as population increase, shifts in the proportion of urban and rural populations, and variations in urban and rural household sizes, significantly influence energy consumption in the residential sector. This includes energy usage for lighting, cooking, and space cooling.

From a statistical viewpoint, Ghana's population has increased from 24.7 million in 2010 to 30.8 million in 2021, with a corresponding total energy use of 5,537 ktoe in 2010 to 9,345 ktoe in 2021 (GNETF, 2022). Despite a decline in growth rate from 2.5% between 2000 and 2010 to 2.1% between 2010 and 2021, projections indicate that the country's population will reach 50 million by 2050, resulting in a rise in energy demand (GNETF, 2022). Growth in GDP, changes in personal disposable income, and changes in the structure of the economy (that is, shares of industry, services, and agriculture in total GDP) also influence the level of energy demand in the country. The country's GDP in 2010 was USD 32.2 billion, increasing to 79.1 billion in 2021. The structure of the economy has also changed from an agricultural sector-led economy to a service sector-led economy, which accounted for the largest share of 48.9% of total GDP formation in 2021 as compared to 42.6% in 2010. There is a positive relationship between disposable income and the ownership and usage of energy-use equipment like autos and electrical appliances. These gadgets contribute to the demand for energy.

The policies of the government, such as the National Electrification Scheme, Accelerated Industrialisation and Agricultural Programs, and the promotion of productive uses of energy, also contribute to the growth of energy demand. The share of the population with access to electricity increased from 64.4% in 2010 to 87% in 2021 (EC, 2022). Nevertheless, the implementation of energy efficiency initiatives also resulted in a decrease in energy waste and led to a decline in the total increase in energy demand. The economy's energy intensity decreased from 73.8 toes per million US dollars in 2010 to 71.8 toes per million US dollars in 2021, reflecting this shift.

Energy Demand Situation in Ghana

Final energy consumption by fuel type

The National Energy Statistics report in 2023 indicated that the overall final energy consumption experienced a consistent increase, rising from 5,470 ktoe in 2000 to 8,537 ktoe in 2022. This represents an average yearly rise of 2.2%. Nevertheless, there was a 0.2% rise in the overall final energy consumption in 2022 in comparison to 2021. Electricity consumption has steadily grown at a continuous rate of 4.3%, hitting a total of 1,509 kilotonnes of oil equivalent (ktoe) in the year 2022. On the other hand, there was a decline in petroleum consumption from 4,641 ktoe in 2021 to 4,318 ktoe in 2022. This signifies a decrease of 7%. The rate of biomass consumption has been decreasing by 0.7% annually, resulting in a decline from 3,432 ktoe in 2000 to 2,940 ktoe in 2022.

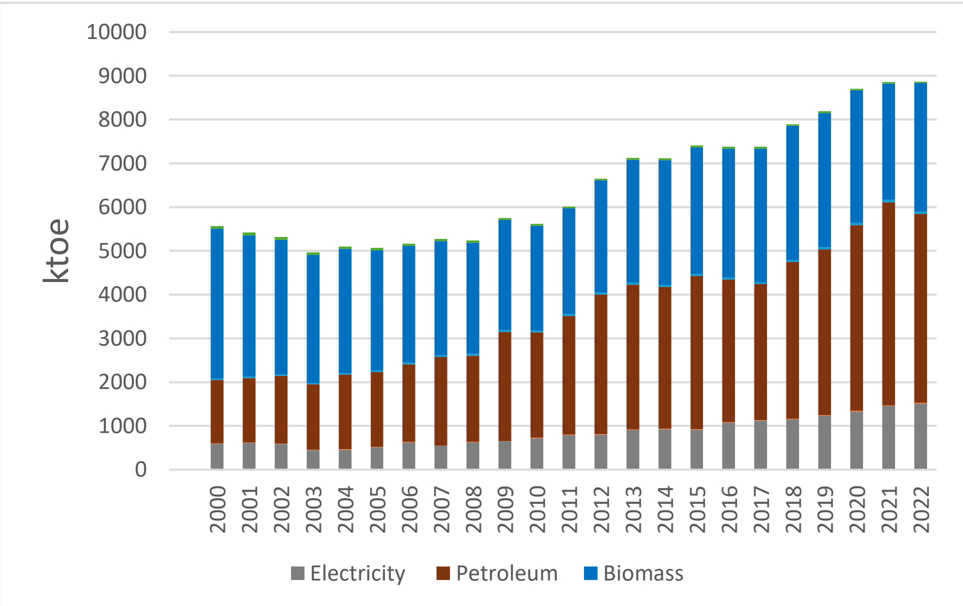

Figure 2: Total Final Energy Consumed by Fuels (ktoe)

Source: Authors construct (2024)

Total final consumption by sector

The industry, transport, and residential sectors are the main drivers that contribute to overall energy consumption (Ackah, 2018). The energy consumption of Ghana's industrial sector experienced an annual growth rate of 3.8%, resulting in 1,656 ktoe in 2022, as reported by the Energy Commission in 2023. In addition, the energy consumption of the transport sector experienced a growth rate of 5.3% year, reaching 3,535 ktoe in 2021. However, it subsequently decreased by 6% to 3,322 ktoe in 2022. On the other hand, there was a decrease in household consumption, with a growth rate of 0.1%, from 3,390 ktoe in 2000 to 3,320 ktoe in 2022. From 2000 to 2022, the service industry maintained an average annual growth rate of approximately 5.3%. In addition, the agriculture sector experienced a consistent gain in consumption throughout time, but then saw a decrease in 2022.

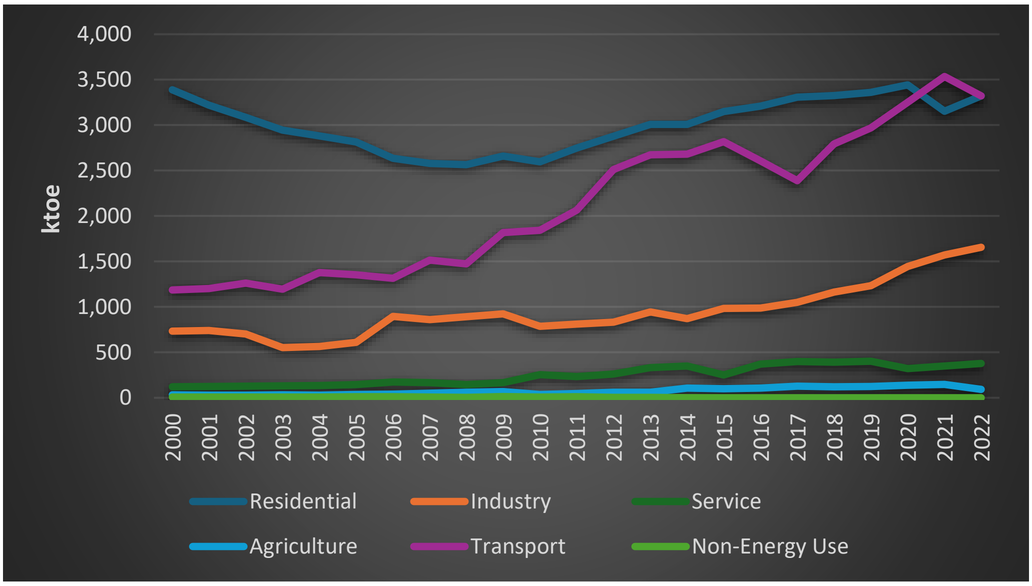

Figure 3: Final Energy Consumption by Sectors (ktoe)
Source: Authors Construct (2024)

Energy Resources in Ghana

Fossil fuel resources

In the late 19th century, Ghana initiated the search for crude oil by building onshore wells near the border with La Cote d'Ivoire. In 1965, the Ghana geological survey department, with technical support from the Romanian government, conducted exploration drilling near the cities of Anloga and Atiavi, situated on the southeastern coast of the country (McCaskie, 2008). The Signal-Amoco partnership discovered the Saltpond field in 1970. Kesse (1986) first estimated the appraisal potential of the Saltpond field to be 3600 barrels per day. Nevertheless, the consortium surrendered the concession at the conclusion of 1979. The Saltpond Offshore Producing Company (SOPCL) is the current operator of the oil field. In 1974, Phillips, Zapata, Oxoco, and the Agip consortium of corporations succeeded in discovering natural gas in Cape Three Points. Nevertheless, there was no official evaluation of the reserves in this discovery (Kesse, 1986).

Despite previous discoveries, significant amounts of oil and gas were extracted in 2010 after Tullow Oil and Kosmos Energy identified the Jubilee Field in 2007. The estimated reserves of the Jubilee field are up to 3 billion barrels of sweet crude oil, according to Brenya et al. (2015). According to Ghana's 2014 Energy Supply and Demand Outlook, the initial output of 80,000 barrels per day rose to a range of 110,000 to 115,000 barrels per day by the first quarter of 2013. Additionally, the report anticipated that natural gas production would reach approximately 140 million cubic feet per day. Apart from the Jubilee Field, there are two other major fields, namely, Tweneboah-Enyenra-Entomme (TEN) Field and Sankofa-Gye Nyame Field. In 2009, researchers discovered the TEN field, situated approximately 20 kilometres west of the Jubilee Field. TEN Field is an associated gas reserve estimated at 340 billion cubic feet (GNPC, 2015). The Sankofa-Gye Nyame Field is also located about 60 km offshore Cape Three Points (OCTP). It holds an estimated reserve of about 1.45 trillion cubic feet of non-associated gas. The World Factbook in 2016 reported that, Ghana is positioned as the 45th country in the world with proved reserves of crude oil, and as the 74th country with confirmed reserves of natural gas. Based on the country fact file of the Central Intelligence Agency, the confirmed amount of crude oil reserves as of January 2015 is 660 million barrels (MMbbl), and the amount of natural gas is 22.65 billion m3 as of January 2014. However, Ghana has not yet been acknowledged as possessing any coal resources suitable for commercial extraction.

Renewable Energy Resources

Solar resource

Ghana is situated between the latitudes of 4°44’N and 11°11’N. The western and eastern boundaries are located at longitudes 3°15$'W$ and 1°12$'E$ respectively (Awopone, 2021). The nation possesses a tropical environment characterised by high temperatures and humidity. It spans a land area of roughly 238,539 square kilometres. The country has a plentiful solar resource that is consistently available throughout the year in all regions. The distribution of solar resources across the country exhibits small variations, with the greatest abundance found in the Northern Savannah region. The direct conversion of solar energy into electricity is the most auspicious renewable power source globally (Awopone, 2021). According to estimates, the solar radiation available worldwide has the potential to generate 1700 terawatts (TW) of electric power.

Just 1% of this amount would be sufficient to supply the current global demand for electricity (Akbari & Shahsavari, 2018). Ghana experiences consistently high sun irradiation throughout the year, having an average ground measurement ranging from 3.92 to 6.11 kWh/m2 per day (Awopone, 2021). At this radiation intensity, the overall energy capacity is immense, approximately 100 times the current energy use, even accounting for a 10% recovery rate.

Hydropower resource

Hydropower is the second most significant electricity source globally, following fossil fuels. It accounts for around 17% of global electricity consumption (Sternberg, 2010). The Akosombo and Kpong hydropower facilities generated the majority of Ghana's grid electricity prior to early 1998. However, subsequently, Miescher & Tsikata (2009) added thermal energy to the national energy mix. The country possesses numerous sites that are considered appropriate for the establishment of large and medium-sized hydropower facilities, with an additional total capacity of over 900 MW of electricity (Dernedde & Ofosu-Ahenkorah, 2002). Furthermore, researchers have identified more than seventy minor hydroelectric sites. These sites have a total estimated capability of approximately 4 to 14 MW when they are connected to the grid, as stated by (Kemausour et al., 2011).

Wind energy

Islam et al. (2014) ascertain that, wind energy is now experiencing rapid growth and is considered one of the most rapidly expanding RE sources globally. Despite having abundant potential, Ghana has not yet successfully utilised this valuable renewable resource for generating power on the grid. As stated by Paska et al. (2009), the average wind speed at a height of 50 m from the coastline of Ghana, measured in the direction of the wind, is approximately 5.5 meters per second (m/s). Wind measurement for meteorological and agricultural uses in Ghana started in 1921, as documented by Nkrumah (2009) and cited by Essandoh et al. (2012).

However, wind observations, specifically intended for the development of utility-scale wind power, began in 1999. The Global Environment Facility (GEF) and the UN Environment Programme (UNEP) provided financial support for the inception of Ghana's SWERA Project in 2002. The Energy Commission of Ghana and the former Ghana Meteorological Service Department (GMSD), now known as the Ghana Meteorological Agency (GMA), managed this project. The National Renewable Energy Laboratory (NREL) of the USA created the Wind Map of Ghana during the Ghana SWERA Project in 2002, primarily categorising Ghana's wind resources as moderate winds along the coast and in specific locations.

Ashanti, Greater Accra, and the Eastern and Northern regions of Ghana have favourable wind conditions. These regions have a few areas with favourable wind, as well as some spots with excellent wind speed. Additionally, the Volta Region, particularly along the Ghana-Togo border, has some excellent wind speed spots, as well as some good windy sites within it. Finally, Ghana's Brong-Ahafo region also has some excellent windy sites. The Energy Commission of Ghana conducted subsequent research and identified Mankoadze, a coastal town in the Central Region of Ghana, as having abundant wind energy potential (Essandoh, Osei, and Adam, 2014).

The Volta River Authority is collaborating with Vestas and El Sewedy, two wind developers, to establish 150 MW of wind power in four specific locations in the southern region of the country. The Volta River Authority has identified these sites, namely Anloga, Anyanui, Lekpogunu, and Akplabany, based on their wind resource potential (VRA, 2021). In addition to this, the Ningo-Prampram district in Ghana, West Africa, is currently developing the Ayitepa wind farm, which will have a capacity of 225 MW. The wind farm is located around 60 km east of Accra city.

Biomass

The term “biomass” refers to organic material capable of being transformed into fuel. This resource encompasses both wood and wood waste, including agricultural crops and residue, logging waste, and wood processing waste, as well as animal waste such as livestock and poultry waste. Poor nations widely use biomass as a substitute energy source for cooking and other domestic tasks (Islam et al., 2014). In Ghana, particularly in rural regions, biomass such as charcoal and firewood are the primary sources of fuel for cooking. Nevertheless, the potential for generating electricity from biomass remains largely unexplored in Ghana. Globally, people are increasingly turning to biomass as a clean and renewable alternative to fossil fuels. Concerns over the greenhouse effect, high costs, and diminishing sources of fossil fuels are driving this shift (Duku & Hagan, 2011). Nevertheless, in Ghana, there is a progressive decline in the use of biomass resources and a rise in the use of petroleum products as the predominant energy source.

Plant biomass captures carbon dioxide from the atmosphere and converts it into energy as it grows. When the biomass decomposes or burns, it subsequently emits carbon dioxide into the environment (Paska et al., 2009). Consequently, employing biomass for power generation will lead to almost negligible carbon dioxide emissions. Ofori-Boateng and Mensah (2013) stated that while the cost of building plants to convert MSW into energy is high, it is extremely feasible to consider MSW as a viable alternative for power production in Ghana. Arthur et al. (2011) conducted a study in Ghana to assess the viability of biogas as a RE source. Their research revealed the abundance of biomass resources available for biogas production.

Development of Energy Needs in Ghana

Historical trends in the energy sector

In the past decade, Ghana, like many other African nations, has experienced a rise in energy demand that has exceeded the available energy supply. After Ghana gained independence in 1957, there was a strong desire to undertake a massive industrialisation effort, which involved constructing roads, schools, hospitals, and factories. This endeavour necessitated a dependable source of electricity. To successfully construct a dam, the Ghanaian government secured funding from the World Bank and the United States, specifically VALCO. As a result, the Volta River Authority (VRA) was founded in 1961 with the responsibility of generating energy using the hydroelectric power of the Volta River and constructing the Akosombo project (Volta River Authority, 2019). The electricity demand reached its highest point at 540 GWh in 1968, mostly driven by many causes such as growing industrialisation.

Domestic power consumption experienced almost six-fold growth, rising from 540 GWh in 1968 to 3917 GWh by 1976. However, due to the deteriorating economy in the late 1970s and early 1980s, the country’s electricity consumption dropped from 3917 GWh in 1976 to 3429 GWh in 1978, and it further declined to approximately 1151 GWh in 1984 (Meng, 2019).

Kuamoah (2020) built the Kpong Hydroelectric Project in 1971 to meet the growing power demand, adding an additional 160 MW of capacity. Nevertheless, the initial energy shortage in 1984, exacerbated by a significant drought in 1983, hindered the power-generating capacity of the Akosombo dam (Institute of Statistical, Social, and Economic Research, 2005). The dam received an inflow between 1982 and 1984 that was less than 15 percent of the anticipated total.

Consequently, they implemented electricity rationing and reduced the supply to neighbouring nations, Togo and Benin. The power supply had a decline from 5180 GWh in 1981 to 1670 GWh in 1984, whereas usage over the same period declined from 4652 GWh to 1151 GWh. Power consumption rose significantly, from 2083 GWh in 1985 to approximately 4780 GWh in 1990. In 1998, due to insufficient rainfall and inflows into the Volta Lake, a power crisis occurred. This led to another round of power-rationing. In 1998, users' electricity supply decreased to approximately 4942 GWh. During the same period, consumption dropped from 5110 GWh in 1991 to 4965 GWh in 1998, almost exceeding the available electricity supply for that year.

Ghana's installed grid generation capacity is currently 5,454 MW as of 2022, indicating a yearly average growth rate of 8%. In the same vein, the overall reliable power generation capacity rose from 1,358 MW in 2000 to 1,940 MW in 2010, and further increased to 4,843 MW in 2022 (EC, 2022). On April 7, 2021, Ghana reached its greatest demand (system peak load) of 3,206 MW. The installed generation capacity of the grid consists of 1,580 MW from hydropower and 3,438 MW from thermal electricity, according to the EC's report in 2022.

Development of renewable energy sources in Ghana

The mid-1960s saw the construction of the hydroelectric dam, which marked the inception and advancement of RE sources in Ghana. Prior to that period, the primary means of generating power was a limited number of independent diesel generators scattered throughout the nation. Approximately forty years later, hydropower potential became the dominant and widely accepted primary source of energy supply, making a significant contribution to the country's energy mix. As a result, Ghana officially authorised the Volta River Authority to produce electricity in 1961 (Ackah & Asomani, 2015). Ghana has emerged as the focal point of rapid urbanisation in West Africa, with notable advancements in education, technology, and business. Industrialisation has led to an increase in the country's demand for electricity. Consequently, the government and public sector are actively searching for alternate RE sources to supplement the prevailing hydropower energy supply, as exemplified by the Akosombo Dam on the Volta River.

Renewable energy includes a wide variety of sources and technologies, with certain ones being more popular for their environmental friendliness than others are. For instance, several individuals regard solar and wind power as more desirable than hydropower generated by large dams, due to the potential release of GHGs (methane), the promotion of diseases associated with stagnant water, the displacement of populations, and the contribution to drought. On the other hand, Kuamoah (2020) commends large-scale hydropower for its ability to increase electricity generation. Ghana should adopt RE sources due to their inherent sustainability and perpetual availability, in contrast to finite fossil fuel reserves.

The government of Ghana has established certain objectives for its energy industry, in accordance with worldwide patterns. The objective is to ensure universal access to electricity by the conclusion of 2026. The government has a vision to ensure that all sectors of the economy have dependable ES that are of superior quality and have the capability to export power to adjacent countries. The Ministry of Energy (2010) has recognised RE sources as a highly promising solution for enhancing Ghana’s energy security and environmental management, with the aim of mitigating the adverse impacts of climate change.

The Renewable Energy Act of 2011 (Act 882) was enacted to establish a set of rules and financial rewards that would encourage private sector investment and encourage a sustainable and effective use of RE. The Government of Ghana has set a goal to reach a 10% share of RE (excluding large hydro) in the electricity generation mix by 2026. To meet the RE goal, the Ghanaian government provides substantial assistance for RE investments. However, in 2019, the combined capacity of renewable electricity installed on both the grid and off-grid was around 78.6 MW. In 2019, on-grid electricity generation accounted for 42.6 MW, which is approximately 0.8% of the country’s total electricity generation (Energy Commission, 2020). This statistic does not include community PV systems, such as community solar PV systems used for water pumping, solar PV systems used for irrigation, and systems used for residential and institutional purposes.

As the seventh Sustainable Development Goal (SDG) says, everyone should have access to affordable, reliable, and long-lasting energy by 2030. For Ghana’s socioeconomic progress, it is important to put RE source development and use at the top of the list (Aboagye et al., 2021). RE systems are currently being promoted for both on-grid-connected power plants and off-grid connected systems used in residential and institutional settings, community water systems, and irrigation.

Ghana's Policies Towards Sustainable Transition

Despite the modest efforts made since the Paris Agreement, global emissions levels are still increasing and falling far short of the agreement's goals. The UN Climate Change Conference in Glasgow (COP26) affirmed the need to accelerate actions to reduce carbon dioxide emissions to reach net zero. World trade is also shifting towards green markets (commodities that are manufactured using clean energy resources). International funding of national programmes and projects favours green economies. Therefore, Ghana and the rest of Africa need to take advantage of their green energy resource potential (hydro, uranium, biomass, geothermal, wind, tidal waves, and solar) and abundant natural resources (diamond, gold, platinum, copper, cobalt, iron ore, phosphate, bauxite, copper, silicon, and titanium) to strategically position themselves for the green trade.

Because of that, Ghana has initiated and implemented several policies to help transition our economy from a fossil fuel-based to a renewable based economy. Although the formulation of these policies did not consider net zero targets, they serve as a sufficient foundation for Ghana's energy transition and contextualize ongoing efforts to reduce emissions. These policies and measures include the Ghana Integrated Power Sector Master Plan, the Renewable Energy Master Plan, the Gas Master Plan, Ghana's Updated Nationally Determined Contribution under the Paris Agreement (2020–2030), the Ghana Trade Policy, the National Infrastructure Plan by the National Development Planning Commission (NDPC), the Policy on Zero Gas Flaring, the National LPG Promotion Policy, the 2020 National Transport Policy, the Energy Transition and Critical Minerals in Ghana, Diversification Opportunities and Governance Challenges, and Energy Efficiency Regulations.

In Ghana, the implementation of the Paris Agreement on Climate Change is carried out using three key administrative and legally binding documents: The Nationally Determined Contributions (NDCs), the Conference of Parties (CoPs) Agreements, and the National Energy Transition Framework (2022–2070).

Ghana National Energy Transition Framework (2022 – 2070)

The National Transition Framework aligns with the country's development strategy stated in Article 36(1) of the 1992 Constitution. This article mandates the government to effectively handle the national economy in order to optimise the well-being of the population. Ghana's GNETF aims to decrease GHG emissions by implementing decarbonisation strategies and improving energy availability, security, and efficiency. The Energy Transition Model (ETM) for the GNETF is based on three primary assumptions to achieve a net zero target by 2070, with a cost of USD 562 billion based on the 2021 baseline figure. The initial presumption is of an economic nature.

The annual growth rate of gross domestic production would be 5%, resulting in an increase from USD 79.08 billion to USD 863.69 billion. The second premise pertains to demographics. If Ghana's population were to grow at an annual rate of 2%, it would reach 72.2 million, up from its current population of 30.8 million. According to Sefa-Nyarko (2024), the third assumption is that the proportion of industrialisation in urban and rural areas would increase from 56% to 85% at a yearly rise of 1%.

The global transition from fossil fuels to cleaner sources of energy presents opportunities and threats towards the realization of this vision, as it promises to change the economic and social dynamics of the country with medium- to long-term consequences for the welfare of the citizens. The Ministry of Energy, in partnership with other sector ministries such as Transport, Environment, Science and Innovation, Finance, Lands and Forestry, Water, and Sanitation, has developed this plan to outline Ghana's transition pathways towards SD, with the aim of maximising the well-being of its citizens. The Plan aims to:

i. identify feasible strategies for the country to achieve carbon-neutrality within a reliable and secure energy system.
ii. Seize the opportunity to achieve a just and equitable transition to clean energy, considering the country's dependence on industries that produce high levels of carbon emissions for economic development.
iii. Assess the effects of energy transition on the economy, namely in terms of infrastructure, government revenue, employment, and social development.
iv. Formulate medium to long-term objectives and strategies to attain a carbon-neutral economy.
v. Assess the expenses associated with executing the strategy and determine potential sources of funding for achieving the specified goals.

However, despite the detrimental effects, wasted time, and the government's pledges to reduce the usage of filthy cooking energy, the problem has continued to exist. Many urban households consider charcoal to be a dependable, cost-effective, and efficient source of energy for cooking, in comparison to other options. In 2017, 68% of charcoal users in Ghana lived in urban areas, which was a decrease from 76% in 2006 (Sefa-Nyarko, 2024).

Chapter Summary

This section reviewed the technology acceptance model and energy efficiency. Under the energy efficiency theory, we discussed the rebound effect and the energy efficiency paradox. The concepts of energy demand, consumption and supply situation in Ghana, energy resources in Ghana, and disaggregated energy demand were reviewed. There was a review of empirical research on the effects of different adoption scenarios on final energy demand across different sectors. The study looked at key uncertainties and sensitivities in the scenario analysis, especially when it comes to technological advances and changes in regulations. It also looked at the effects of modern energy adoption in Ghana's energy, environment, and socio-economic development, as well as possible future energy landscapes under different adoption scenarios to help make decisions and come up with policies.

CHAPTER THREE

RESEARCH METHODS

Introduction

This chapter provides a comprehensive examination of the method, processes, and procedures employed in conducting this study. The study's methods and approaches have been examined and categorised under the following subheadings: research paradigm, research methodology, study design, model specification, data sources, and ethical considerations.

Research Philosophy

This study's philosophical perspective aligns with the positivist approach to research. Positivism is based on quantifiable observations that lead to statistical analyses. Positivists believe that there is a single reality that is possible to measure and understand. This assumption makes them more likely to use quantitative methods in their research (Cresswell, 2013). As stated by Crowther and Lancaster (2012), in positivist studies, the researcher remains impartial and does not consider human interests as part of the study. Only through objectivity can we comprehend and evaluate a truth in a scientific manner. Pring and Thomas (2004) referred to this notion, saying, "One purpose of research is to explain what the case is or what has happened". A reason for seeking explanations may be to predict what will happen in the future or what would happen if there were to be certain interventions. Therefore, the researcher conducted the study based on predetermined beliefs and information about the outcome. Thus, using the available data in the Ghanaian context, we can determine the impact of the adoption of modern ES and technology on final energy demand.

Research Approach and Design

The researcher chose to use the quantitative approach for the investigation based on its nature and philosophical foundation. The study employs a quantitative research approach, notably utilising the cross-sectional research design, to accomplish the research aims. The quantitative research strategy, as defined by Burns and Grove (2010), is an objective and efficient method that systematically describes, examines, and tests correlations between variables. The design of this study is objective and indisputable, ensuring that the results and outcomes are dependable, reproducible, valid, and generalisable. Therefore, the application of this approach in studying ensures that the results are reliable, can be replicated, and are open to additional empirical examination.

Model Specification

The study utilised the Model for Analysis of Energy Demand (MAED-2) built by the International Atomic Energy Agency in 2006. The MAED was implemented to assess various choices for energy sector expansion and predict future energy requirements. The MAED model software consists of two distinct modules: MAED_D and MAED_EL. The MAED_D analyses data on the social, economic, and technological aspects of development and computes the overall energy requirement for the specified time periods. The MAED_EL module utilises the aggregate yearly electricity demand for each sector (computed in MAED_D) to ascertain the overall electricity power requirement for each hour of the year, also known as the hourly electric load. This load represents the demand placed on the power system being studied.

The MAED_D model is a concise representation of the key features and organisation of the MAED_D model.

The MAED_D model forecasts future energy consumption by considering medium to long-term projections of socio-economic, technical, and demographic changes. The model establishes a systematic relationship between the precise energy demand for manufacturing different commodities and services, as described in the model, and the related social, economic, and technological elements that influence this demand. The model divides energy demand into various end-use categories, each of which corresponds to a specific service or the manufacture of a particular object. The demand for goods and services is influenced by various factors such as population growth, population density, household usage of electrical appliances, transportation preferences, national economic priorities, advancements in equipment efficiency, and the adoption of new technologies or energy sources.

The anticipated future trends for these influencing factors, which make up ‘scenarios,’ are externally introduced. Understanding these influential aspects enables the development of different energy consumption classifications for each analysed economic sector. The model offers a methodological accounting framework for assessing the impact on energy demand resulting from changes in economic conditions or the population’s standard of living.

Regarding demand estimation and methodology, market penetration and end-use efficiency influence the final determination of energy demand, which is based on usable energy. Furthermore, the estimation of demand is achieved by establishing a correlation between energy intensity and the amount of economic activity. The demand of each subsector is determined and then aggregated into the total final demand using a uniform accounting framework.

The MAED model provides a detailed analysis of the sectoral distribution and composition of energy consumption. It specifically focusses on four key sectors: industry, transport, service, and household. The primary sectors are further separated into sub-sectors, with industry being divided into agricultural, construction, mining, and manufacturing; transportation being divided into goods, urban, and intercity; and homes being divided into urban and rural. Both the industrial and service sectors encompass the energy intensity of motor power, electricity, and thermal utilisation, along with efficiency and market reach. The transportation sector encompasses the energy intensity and load factors of freight, intercity, and intracity transportation. The residential sector encompasses several components such as space heating, water heating, cooking, air conditioning, and domestic appliances in both urban and rural residential buildings. The service sector primarily focusses on space heating and air conditioning.

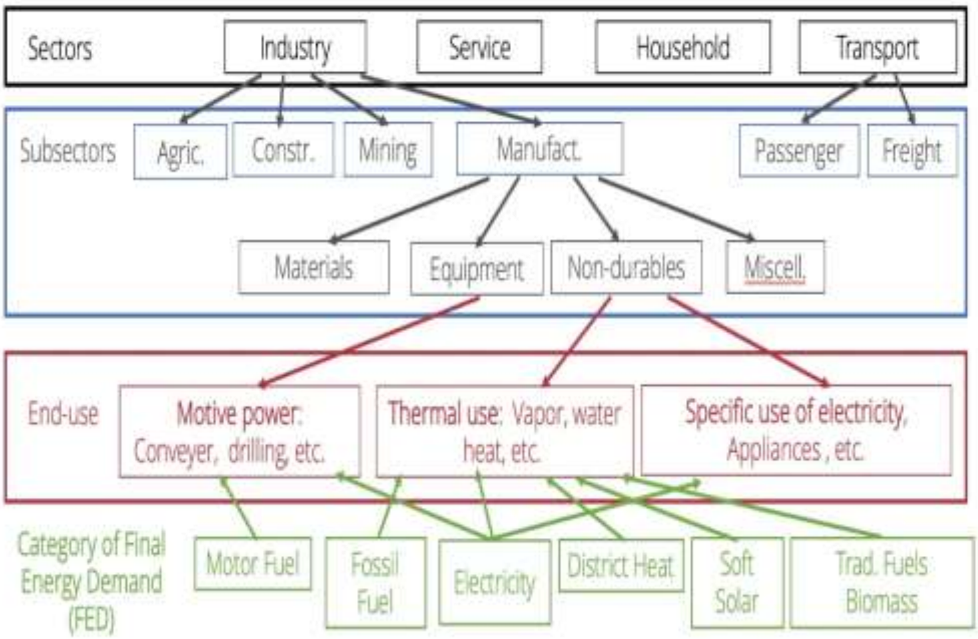

Figure 4: Decomposition in MAED

Source: Climate Compatible Growth (2023)

The structure of the model

The MAED_D modelling technique is outlined below.

Step 1: Establish the base and reference years. Typically, the base year is the year in which all economic indicators show positive conditions.

Step 2: Prepare and preprocess the data.

Step 3: Formulating the baseline scenario and alternative scenarios.

Step 4 involves conducting scenario analysis and implementing the MAED_D. Examine and validate the outcomes of the model for the final energy requirements in each industry and fuel category, using the consumption data from the base year.

Step 5: Analysis of findings and implications for policy. The results will be compared to earlier studies and policy recommendations will be given.

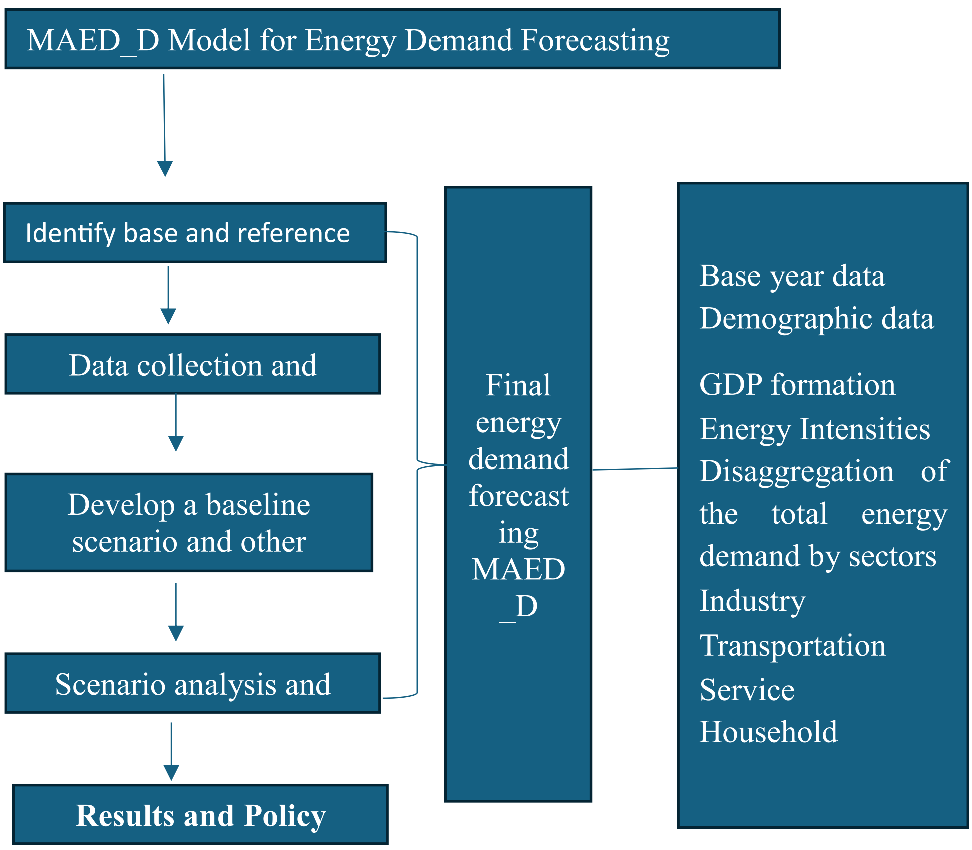

Figure 5: The structure of the MAED_D

Source: Author's Construct (2024)

Model formulation

To perform calculation of the Final Energy Demand (FED) by each of end-use, a corresponding set of equations are used in MAED. All equations have the same form.

Energy Intensity (EI) as measured by the quantity of energy required per unit output and Energy Efficiency (**η**) as measured in the improvement of the level of service provided with reduced amounts of energy inputs.

$$\mathbf{EI} = \frac{\mathbf{FEC}}{\mathbf{PSP}} = \frac{\text{Final Energy Consumption}}{\text{Product Service Provided}} \qquad (\mathbf{1})$$

The Final Energy Demand (FED) in any specific year in the future is calculated as a product of the Driving Parameter (DP) in a corresponding future year and the Specific Energy Consumption (SEC) per unit of Driving Parameter (DP) in future years.

When the Driving Parameter (DP) is the production of monetary units, value added, or GDP, the Specific Energy Consumption (SEC) is the Energy Intensity $(EI)_{-t}$

$$FED_t = SEC_t \times DP_t \qquad (\mathbf{2})$$

$$FED_t = El_t \times GDPt \qquad (\mathbf{3})$$

Where **FED** is the Final Energy demand in year t and **GDP** is the Driving Parameter in year t

The calculation of the demand for Motor Fuels (MF) and Specific uses of Electricity (ELS), such as lighting and motive power, is based on the measurement of final energy consumption. First, the demand for thermal energy is assessed in terms of its usefulness and subsequently transformed into final energy, taking into account assumptions about the adoption of alternative energy sources (such as traditional fuels, modern biomass, electricity, and fossil fuels) in the market and their efficiencies compared to conventional electricity technologies.

Total Useful Energy (US) for Thermal Energy Use (TU) in Agriculture (AG)

$$US.TU.AG(I) = \sum_{I=1}^{NSAGR} (\mathrm{EI.TU.AG(I)} \times \mathrm{YAG(I)}) \times CFI \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{4})$$

The Average Penetration (P) of alternative energy sources (Modern Biomass) in Agriculture, Construction and Mining (ACM)

$$\mathbf{MBPACM} = \frac{(\mathbf{MBPAGR} \times \mathrm{US.TU.AGR} + \mathbf{MBPCON} \times \mathrm{US.TU.CON} + \mathbf{MBPMIN} \times \mathrm{US.TU.MIN})}{\mathrm{US.TU.ACM}} \ldots\ldots\ldots\ldots\ldots (\mathbf{5})$$

Conversion of useful energy demand for thermal uses to final energy demand in ACM

$$\mathrm{MBAGR} = \mathrm{US.TU.AGR} \times \frac{(\mathbf{MBPAGR}/100)}{(\mathbf{MBEAGR}/100)} \ldots\ldots\ldots\ldots\ldots (\mathbf{6})$$

$$\mathrm{MBCON} = \mathrm{US.TU.CON} \times \frac{(\mathbf{MBPCON}/100)}{(\mathbf{MBECON}/100)} \ldots\ldots\ldots\ldots\ldots (\mathbf{7})$$

$$\mathrm{MBMIN} = \mathrm{US.TU.MIN} \times \frac{(\mathbf{MBPMIN}/100)}{(\mathbf{MBEMIN}/100)} \ldots\ldots\ldots\ldots\ldots (\mathbf{8})$$

Where: MB = Modern Biomass, AGR = Agriculture, CON = Construction, MIN = Mining and ACM = Agriculture, Construction and Mining in the industry sector.

Total Final (FIN) energy demand of Agriculture (AGR):

$$\mathrm{FINAGR} = \mathrm{MFAGR} + \mathrm{ELAGR} + \mathrm{TFAGR} + \mathrm{MBAGR} + \mathrm{SSAGR} + \mathrm{FFAGR} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{9})$$

Energy form share in Agriculture total final energy demand

$$\mathbf{TFAGRS} = \frac{\text{TFAGR}}{\text{FINAGR}} \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(10)}$$

$$\mathbf{MBAGRS} = \frac{\text{MBAGR}}{\text{FINAGR}} \times 100 \quad \ldots\ldots \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{11)}$$

$$\mathbf{ELAGRS} = \frac{\text{ELAGR}}{\text{FINAGR}} \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(12)}$$

$$\mathbf{SSAGRS} = \frac{\text{SSAGR}}{\text{FINAGR}} \times 100 \quad \ldots\ldots \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(13)}$$

$$\mathbf{MFAGRS} = \frac{\text{MFAGR}}{\text{FINAGR}} \times 100 \quad \ldots\ldots \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(14)}$$

Grand total of final energy demand for the country

$$\mathbf{FINEN} = \text{TF} + \text{MB} + \text{ELEC} + \text{SS} + \text{MF} + \text{FF} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(15)}$$

Final energy per capita (MWh/cap):

$$\mathbf{FINEN.CAP} = \frac{\text{FINEN/PO}}{\text{CFI}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(16)}$$

Where: FINEN =Final Energy

TF = Traditional Fuel, MB = Modern Biomass, SS = Soft Solar, FF = Fossil Fuel, MF= Motor Fuel, ELEC = Electricity and CFI is the conversion factor.

The approach used in MAED is based on:

- Simulation model (not optimisation)
- Bottom-up scenario approach (not econometric)
- MAED uses a scenario approach (that is, what would happen if …). This is one of the main advantages of the model, as it allows the analysis of:
- Different socio-economic development policies for the country
- Alternative policies for energy use
- Impact of technological development; and
- Effect of changes in the lifestyle of society.

Through the different scenarios, this model will capture different development trajectories and the influences of the implementation of various policies.

Why the adoption of MAED model

The MAED model is derived from the MEDEE model, incorporating enhancements and adjustments to account for the unique characteristics of energy demand in developing nations. It is considered the most suitable model for analysing energy demand in these countries (IAEA, 2006). The model exhibits a versatile framework that encompasses several aspects such as data, energy consumption trends, sectoral disaggregation, and customer use. The MAED model is capable of computing energy demand across various levels, including sector and subsector, country, and city levels. The study utilised the MAED method to forecast future energy demand for the following reasons.

Table 1: Summary Reasons for the Adoption of MAED Model

Specific Features of Developing Countries	Ghana Specific	MAED Model Scope
Data inadequacy	Inadequate availability of detailed data on specific sectors at the city level	Flexible and necessitates data from a certain base year.
Uncertainties	Absence of comprehensive and long-term policy and strategy	Encompasses both traditional and sustainable energy sources
Disparity between urban and rural areas	Residential units and buildings in ger regions	Can define up to ten categories of dwellings found in both urban and rural households.
Shift from conventional to modern energy sources	There is a significant reliance on fossil fuels and a low utilisation of renewable energy sources.	The user can designate a maximum of eight fuels, but the energy consumed for the purpose of energy conversion is not taken into account.
Poor performance of the power sector	The systems have significant energy loss, and the infrastructure is outmoded.	Covers demand sectors and bottom-up approach
Insufficient deployment of funds and misguided financial support	An energy system that receives significant subsidies and a lack of investment.	The model does not include information regarding pricing and elasticity.
Limited presence of suitable models and institutions	Lack of local energy planning and modelling, as well as insufficient institutional capability and human resources.	The model is compatible with Microsoft Excel and can be effortlessly installed on a Windows PC. It does not require advanced skills.

Source: International Atomic Energy Agency (2006)

Descriptions of scenarios

The study created possible scenarios by considering factors such as the number of households, the adoption of energy use technologies like electricity fuelled vehicle, air conditioning equipment, socio-economic demographics, and the implementation of Government policies like promoting energy efficiency and providing special stimulus packages such as the Gas Master Plan policy and Cylinder Recirculation Model initiative. These scenarios were developed for a 51-year period from 2019 to 2070, aligning with the country's energy future framework. The study formulated three demand scenarios that encompassed the realistic economic, demographic, and government policy projections spanning from 2019 to 2070. These three scenarios can be summarised as follows:

i. Business-as-Usual (BaU) scenario, and

ii. High Economic Growth scenario.

iii. Moderate Economic Growth scenario.

Due to unanticipated changes in the economy and inconsistency in data set as a result of the 2019 COVID pandemic, 2019 was selected as the base year of the model. The favourable nature of the economic conditions in 2019 was the ideal reason why the researcher chose 2019 as the base year of the study. Using 2019 as the base year, the BaU scenario is based on the average and 2019 performance of the country whilst Economic Growth (EG) scenarios take into consideration the objectives of the National Electrification Masterplan, Energy Efficiency Plan, National LPG Promotion Policy, Distribution of Biomass Stove, actions already taken and those planned or proposed to be taken by the government such as one district on factory to achieve a relatively higher economic growth. As such the EG scenario is based on the Ghana's National Energy Transition Framework long-term objectives (2022 – 2070).

Business-as-Usual (BaU) scenario

This scenario was based on the following assumptions:

i. The BaU scenario describes a socio-economic outlook based on the base year data. Population growth rate follows the 2019 growth rate of 2.1% and the GDP growth rate of 5% (average for the country).

ii. The share of urban population would be 56% until 2070.

High economic growth scenario

This scenario was based on the following assumptions:

i. The population growth rate will stabilise at 2.0% from 2030 to 2070 and the urban share of the population will remain at 56% until 2030 and increase at an average of 10% every 10 years until 2070.

ii. Based on Government's socio-economic policy goal to achieve a real GDP per capita of US$ 3,000 in 2024, GDP growth rate would increase to 8.3% in 2030 as projected in the Strategic National Energy Plan of Ghana and increase to 8.8% in the following years.

iii. There would be a penetration of efficient energy technology. For instance, the introduction of electricity fuelled vehicles and 50% of the urban households would be using LPG for cooking by 2050 as projected in the National Energy Transition Framework.

Moderate economic growth scenario

This scenario was based on the following assumptions:

i. The total number of households and share of urban households would remain the same as that for the Business-as-Usual scenario.

ii. The GDP growth rate of the economy would increase to 6.9%, which is an average between the High Economic Growth scenario and the Business-as-Usual scenario.

iii. There would be a penetration of efficient energy technology. For instance, the introduction of electricity-fuelled vehicles as projected in the National Energy Transition Framework.

Variables and Data Source

Table 2: Summary of Main Variables and Data Sources

Variable	Description	Unit	Source
PO	Population	In millions	GSS
UPO.	Urban Population	% of PO	GSS
P. UB	Person/Urban Household	Cap	GSS
P. RH	Person/Rural Household	Cap	GSS
GDP	Gross Domestic Product	In billion $	WDI
Sectoral Shares of GDP			
AGRS	Agric Share	% of GDP	GSS
CONS	Construction Share	% of GDP	GSS
MINS	Mining Share	% of GDP	GSS
MANS	Manufacturing Share	% of GDP	GSS
SERS	Service Share	% of GDP	GSS
ENS	Energy Share	% of GDP	GSS
FINEN	Final Energy Consumptions	In Ktoe	EC

Source: Author’s Construct (2024)

Chapter Summary

This chapter discussed the various methods used for the study. The cross-sectional research designed was used to gather the data for the study. The nature of the study called for the use of simulation model to analyse different alternative policies for energy use in the economy. Possible scenarios was developed based on the size of the urban and rural population, penetration of energy efficient technologies among sectors, socioeconomic characteristics, and implementation of government policies within the economy. Based on that, the business-as-usual scenario, moderate economic growth scenario, and the high economic growth scenario was developed to navigate future energy demand pathways of the economy. The researcher chose 2019 as the base year and adopted the MAED-2 model designed by the International Atomic Energy Agency to project the future final energy demand of the country.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

Introduction

The purpose of this study is to examine the impact of the adoption of modern energy services and technologies on final energy demand in Ghana. Discussions derived from the information gathered are presented in this chapter. The socio-economic characteristics of the country's projections, modelling of different assumption scenarios, and the implications of different adoption scenarios were the main topics of the analysis. Tables and graphs are used to illustrate the projections of the various scenarios of the economy.

Descriptive Statistics

This part presents and discusses the socio-economic characteristics and projections of the data. Specifically, the descriptives are presented in two parts, the total energy supply of the economy and the socio-economic dynamics of the scenarios.

Ghana's Energy Supply

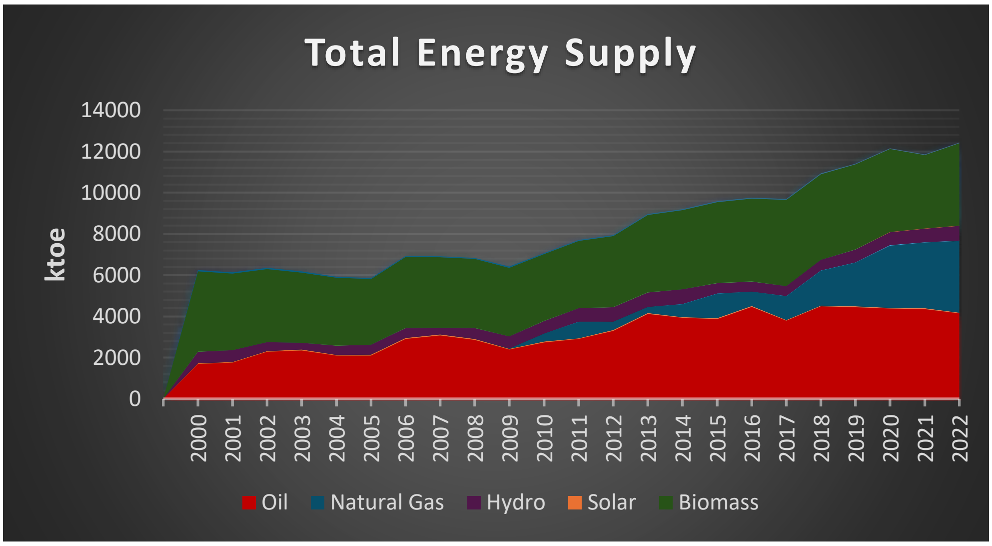

Figure 6: Total Energy Supply (ktoe)

Source: Author's Construct (2024)

To examine the energy demands of the nation, it is necessary to evaluate the current supply situation and understand how to assess the potential options for meeting future economic demands. Based on figure 6, Ghana’s energy mix is reasonably uncomplicated; however, it does face some difficulties. Ghana rely on charcoal, natural gas, petroleum products, electricity, and biomass to meet its energy needs. The supply of energy in Ghana experienced an increase in two different folds, increasing from 6,146 kilotons of oil equivalent in the year 2000 to 12,331 kilotons of oil equivalent in the year 2022. The greater increase in supply is in-line with the average yearly growth of 3.2 percent. The increase in supply was significantly influenced by the increase in biomass supply. In the year 2022, oil emerged as the main energy source accounting for 33.6 percent of the overall energy, followed by biomass (32.4 percent), natural gas (28.2 percent) and hydro with a percentage of 5.7. The contribution of solar energy to the overall energy supply was less than 1%.

From 2010 to 2022, the proportion of natural gas in the overall energy supply has risen significantly, increasing from 5.6% to 28.2%. Conversely, the proportion of hydroelectric power in the overall energy supply declined from 9.2% in 2000 to 5.7% in 2022. The percentage of oil in the total energy supply of Ghana has consistently remained at a higher level (National Energy Statistics, 2023). Per history, Ghanaians have mostly relied on charcoal and firewood, to satisfy their energy needs. However, the percentage of biomass supply in Ghana’s energy has continuously reduced due to the increase in the use of fossil fuels (Ackah, 2021). In 2017, National Energy Statistics of the Energy Commission Ghana, reported that the percentage use of biomass has reduced from 52% of the total primary energy supply in 2009 to 37% in 2016.

Socioeconomic dynamics of the scenarios

This section presents some key drivers that guided the results of the energy demand projections.

Table 3: Population Characteristics of the Base Year

Item	Unit	2019
Population	In millions	30.28000
Population growth rate	% per annum	2.10000
Urban Population	%	56.00000
Person/ urban Household	Cap	3.40000
Number of urban Households	In millions	4.98729
Rural Population	%	44.00000
Person/ rural Household	Cap	4.00000
Number of rural Households	In millions	3.33080
Active Labour Force	In millions	13.98936

Source: Author's Construct (2024)

Table 3 shows the population characteristics of Ghana for the selected base year. The data in the base year shows the total population of 30.28 million, with the yearly growth rate of 2.1 percent. As shown in the table, 56 percent of the population was staying in the urban centres, occupying 4.987 million households. The characteristics of the base year population helped in developing simulation analysis to project the future changes in the population and the total demand for energy for the BaU, MEG, and HEG scenarios.

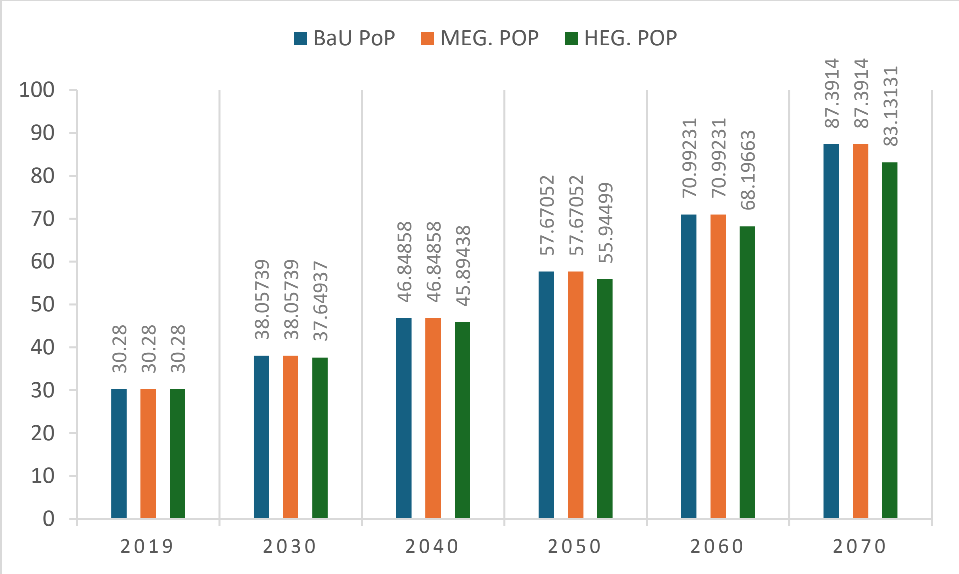

Figure 7: Population Dynamics of the Various Scenarios

Source: Author's Construct (2024)

To determine future demand for energy, it is important to look at how future population would be in all the three scenarios. Figure 7 shows Ghana's population projections in the Business-as-Usual model, Moderate Economic Growth model, and High Economic model. From the projections, the BaU model did not see any significant shifts in Ghana's current national policies and the country's population followed the usual base year growth of 2.1 percent. The characteristics of the BaU scenario reflected a significant change in population from 38.057 million on 2030 to 87. 39 million in 2070. The steady increase in population in the high economic growth model from 38.057 million to 83.13 million in 2070 was as a result of a declined in the population growth rate from the usual 2.1 percent to 2.0 percent in the year 2030. Though the high economic growth scenario depicted an increase in population at a decreasing rate, all the three models exhibited similar patterns in terms of population size as shown in the figure above.

Table 4: Economic Characteristics of the Base Year

Item	Unit	2019
GDP	US$ Billion	68.34000
GDP Growth rate	% p.a.	5
GDP per capita	US$/Cap	2256.93527
Sectorial shares of GDP		
Agriculture	% of GDP	18.13000
Construction	% of GDP	6.40000
Mining	% of GDP	14.90000
Manufacturing	% of GDP	11.20000
Service	% of GDP	47.20000
Energy	% of GDP	2.17000
Total	%	100.00000

Source: Author's Construct (2024)

Since, socioeconomic characteristics such as GDP significantly affect energy demand directly or indirectly, it is relevant to look at the socioeconomic characteristics of the economy when projecting future final energy demand of the economy. From table 4, the country recorded 68.34 billion dollars GDP in the year 2019, with an estimated 5 percent average growth rate. In the same year, gross domestic product per capita amounted to US$/Cap 2256.93. The percentage shares of GDP for the six economic sectors of the country according to the model was also shown in the table. The model used the socioeconomic characteristics of the economy to do simulation analysis to project the changes in GDP for the 51-year period under the established scenarios.

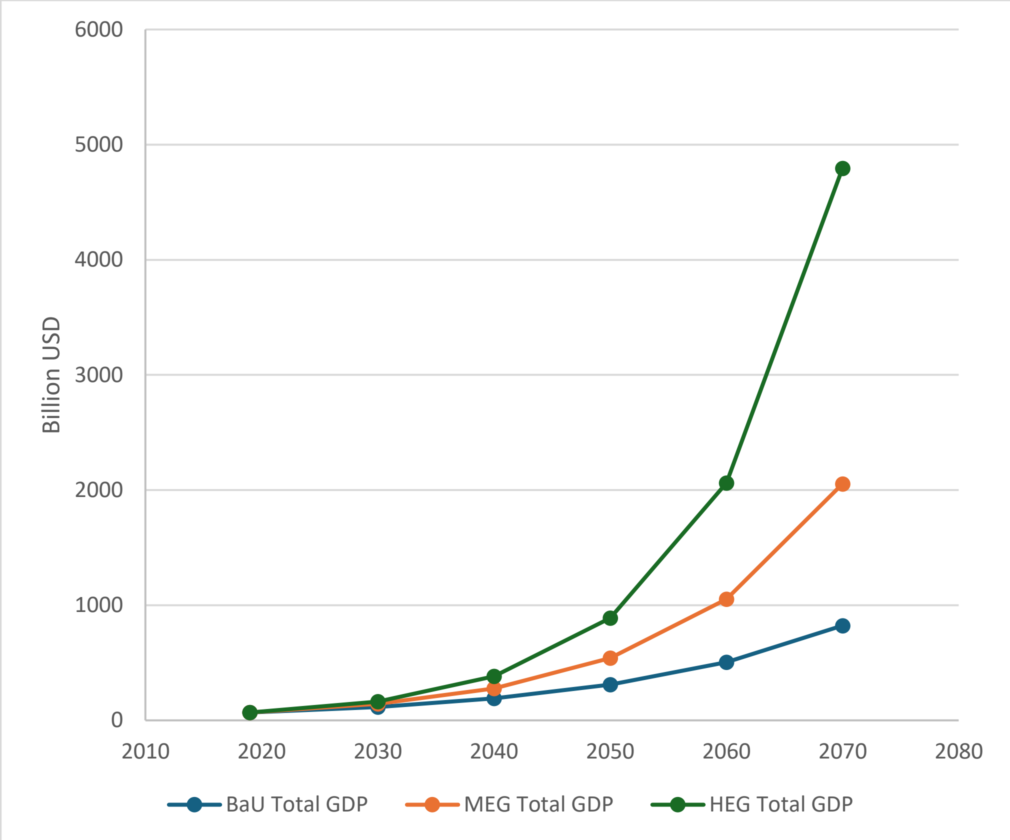

Figure 8: Total GDP Projections Based on Provided Scenarios
Source: Author's Construct (2024)

Figure 8 shows the GDP projections for Ghana from 2019 to 2070 based on current socioeconomic characteristics and energy consumption patterns under the three scenarios: Business-as-Usual, Moderate Economic Growth (MEG), and High Economic (HEG). Under the BaU scenario with no significant changes in current policies and technologies, the 5 percent GDP growth rate generated a steady economic trend with GDP reaching 505.17 and 822.87 billion dollars in 2060 and 2070 respectively. The MEG scenario assumed GDP growth rate of 6.9 percent and the analysis showed an increase in GDP at a moderate pace from 540 billion dollars in 2050 to 2053 billion dollars in 2070.

Again, all the three scenarios showed a relatively close GDP value from (2019-2040). However, differences begin to show up after 2040, with HEG scenario starting to diverge significantly from the BaU and the MEG scenarios. Interestingly, the benefits of aggressive economic and policies coupled with GDP growth rate reaching 8.8 percent resulted in an exponential growth in the GDP for the HEG scenario from 887.49 billion dollars in 2050 to 4794.51 billion dollars in 2070. The results from the GDP projection is in line with Figure 9, which projects the GDP per capita for the BaU, MEG, and HEG scenarios. The trend in the GPD from the scenarios establishes a positive relationship with the per capita GDP as illustrated in the Figure 9.

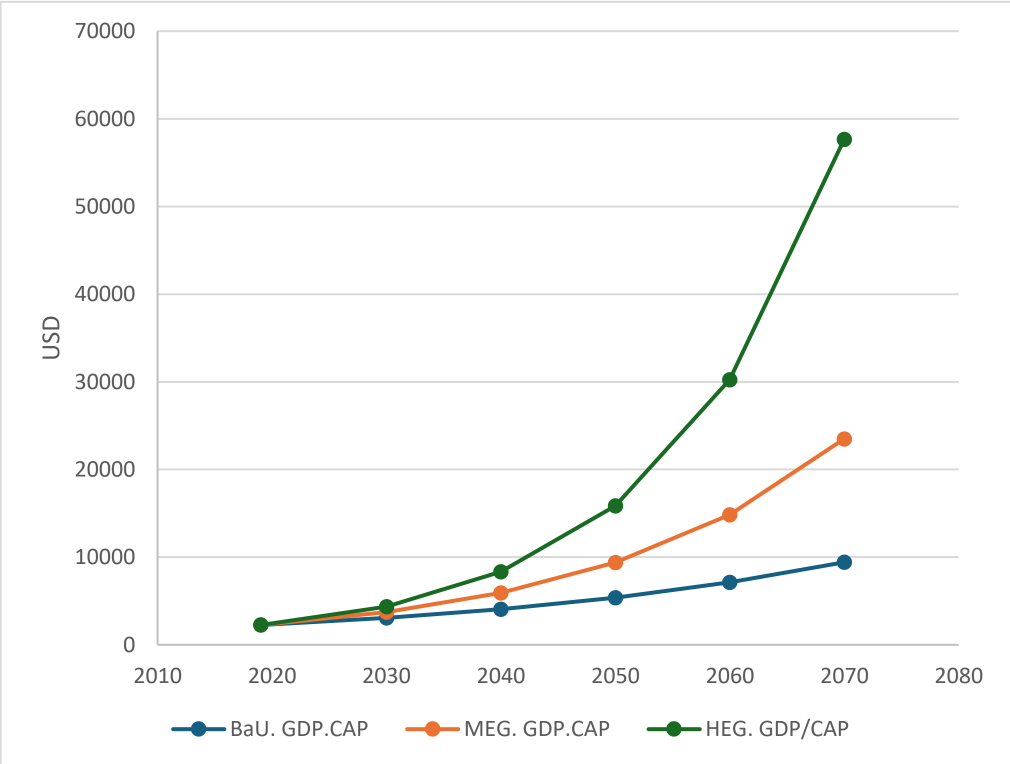

Figure 9: GDP Per Capita for Business-as-Usual, Moderate Economic Growth and High Economic Growth Scenarios.
Source: Author's Construct (2024)

Presentation of Main Results

This section presents the main projections of energy demand by sectors, fuel types, energy per capita, energy intensity, and total final energy demand based on the three scenarios.

Energy Demand Projections by Sectors

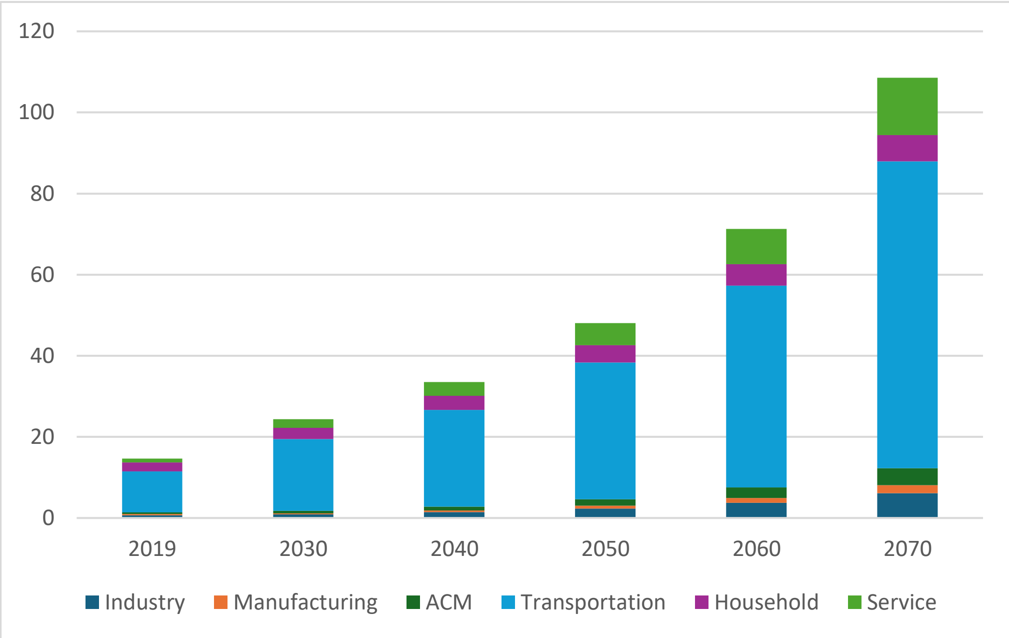

Figure 10: Total Final Energy Demand by Sectors BaU Scenario
Source: Author's Construct (2024)

The first final energy demand results from the model is the total final energy demand at the sectoral level. The total future final energy demand across various sectors of the economy under the Business-as-Usual scenario was illustrated in figure 10. From the results, the BaU scenario projected a steady increase in future final energy demand of the country across all sectors from the year 2019 to 2070. The industry sector total final energy demand would increase from 0.68 GWyr in the year 2019 to 6.13 GWyr in the year 2070. The recorded steady increase in demand was as a result of ongoing industrialisation agenda in the country. In the case of manufacturing sector, there was a projected increase in demand from 0.32 GWyr in 2019 to 1.95 GWyr in the year 2070. Again, the projections for the agriculture, construction and mining (ACM) in the BaU scenario indicated a substantial increase from 0.35 GWyr demand of energy in 2019 to 4.8 GWyr in 2070.

Although there was an increase in the total final energy demand in the residential and service sectors, the increase was not as high as the demand in the transportation sector. The result indicated a high increase in the total final energy demand in the transport sector, surging from 9.45 GWyr in 2019 to 75.6GWyr in 2070. The high increase in demand for energy can be attributed to the considerable development in the economy. As the country continues to grow and urbanizes, the demand for energy to feed the transportation sector will increase in order to meet the energy requirements of companies and the growing population.

It is worth noting that the business-as-usual scenario shows a continuation of existing trends in the energy demands of the country, indicating no substantial changes in government policies and technological progress. From the analysis, energy demand has continuously increased across various, indicating the unlikelihood of occurrence of significant change in the existing trends. This means that without any policy reforms and technological improvements, the country will face many challenges in meeting its future energy needs. The results underscores the significance of industrialisation as a key driver in energy demand and that the use of energy increases in parallel with economic development.

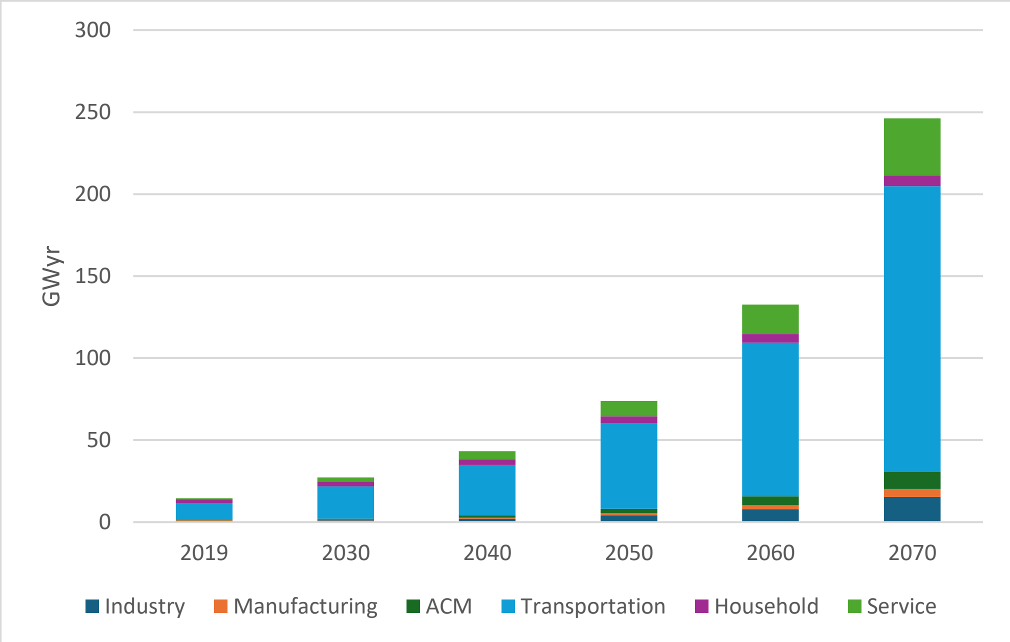

Figure 11: Total Final Energy Demand by Sectors MEG Scenario
Source: Author's Construct (2024)

Figure 11 depicts the total final energy demand by sectors in the moderate economic growth scenario. As indicated in the figure, the total final energy demand was projected to rise from the initial 13.65 GWyr of energy in 2019 to 230.9 GWyr of energy in the 2070. The total final energy demand projected in the moderate economic growth was 100 percent higher than that of business-as-usual model. The high increase in demand for energy in the moderate economic growth model was due to expansion in the various sectors of the economy. To add up to the vigorous economic activities, there was high domestic consumption of energy because of the rise in the living standards of the populace.

The model also assumed a moderate adoption of efficient energy technologies, which depicts a uniform combination of economic development and endeavours to enhance energy efficiency. Again, there was a surge in the economic situations of the country coupled with energy efficient policies that encourages the use of modern energy technologies. Specifically, the transportation sector exhibited a greater increase in the demand for energy compared to the other remaining sectors. However, the population growth rate of the economy mirrored that of the business-as-usual model.

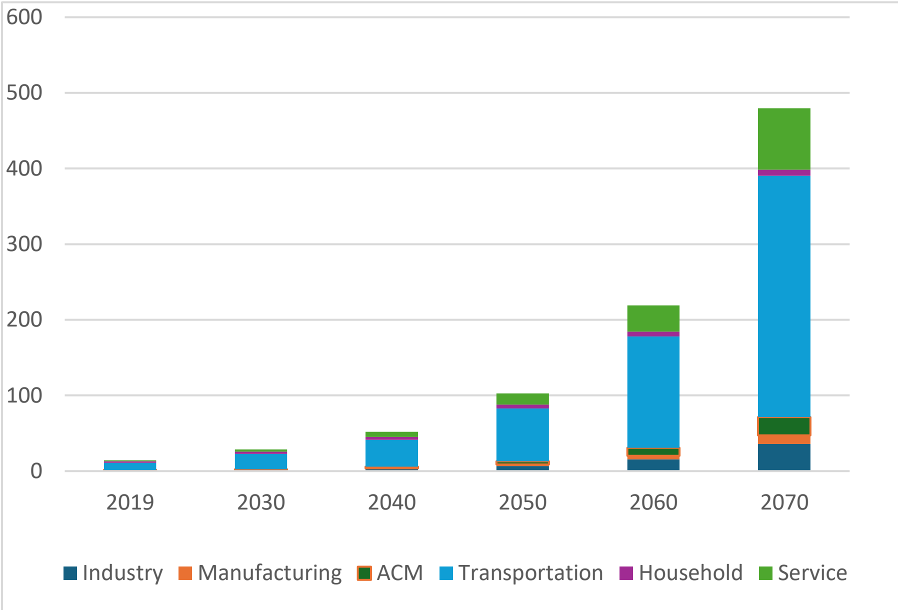

Figure 12: Total Final Energy Demand Projections by Sectors HEG Scenario
Source: Author's Construct (2024)

Figure 12 shows the total future energy demand projections in the HEG model. The model projected the most significant surge in final future demand for energy across all the economic sectors. For instance, the model recorded a significant increase in energy demand in both industry and service sector between the years of 2050 and 2070. Total final energy demand in the agriculture, construction, and mining sectors also recorded a massive surge from 0.35 GWyr of energy in the year 2019 to 24.39 GWyr of energy in 2070, which indicates a high penetration of advanced energy technologies in the HEG model. In the same vein, the total final energy demand in the transportation sector is projected to increase significantly from 9.45 GWyr of energy in 2019 to 319 GWyr of energy in 2070. The rise in demand can be highly associated to a significant increase in vehicle ownership and usage, which would occur as a result of massive economic development.

In general, this model indicates that, 443 GWyr of energy would be needed to feed the growing demand of the economy in the year 2070. The high economic growth model emphasizes the importance of achieving rapid economic development, making substantial improvements in technology, and providing the necessary assistance from the government for the development of efficient energy technologies. To put the model in a proper context, the massive increase in energy demand can be attributed to the rapid increase in urbanisation, increase in the levels of household income, massive industrialisation, and the high usage of energy intensive equipment and electricity powered vehicles. However, the model also emphasizes the possible burden on energy resources and the need for high investments in energy infrastructure and efficiency measures to promote and achieve sustainable development.

Energy Demand Projections by Fuels

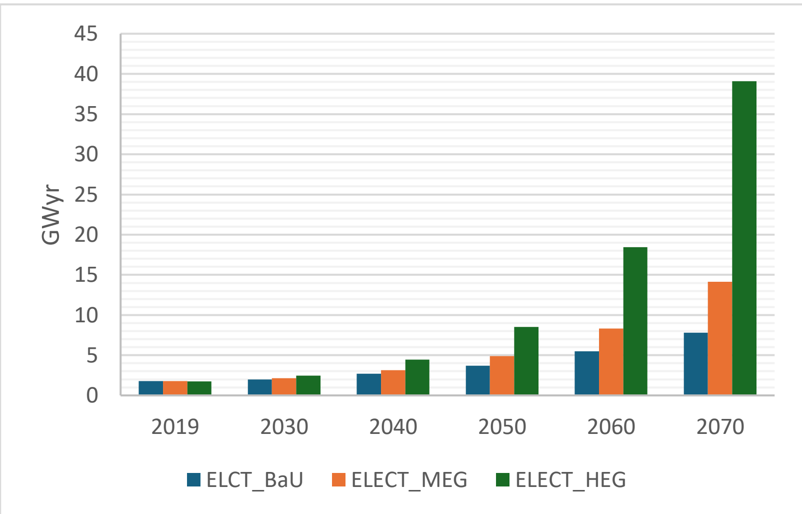

Figure 13: Total Final Electricity Demand Projections in the BaU, MEG, and HEG Scenarios

Source: Author's Construct (2024)

Given electricity's significant role as a secondary energy source and its direct influence on individuals' quality of life, it is critical to examine it in the study. Figure 13 depicts the total electricity demand in the Business-as-Usual, Moderate Economic Growth, and High Economic Growth Scenarios. Total final electricity demand is projected to increase across all levels of the economy in the business-as-usual, moderate economic growth and high economic growth scenarios. The model indicated a consistent growth in total final electricity demand in the business-as-usual scenario from 1.77GWyr of energy in the year 2019 to 7.8 GWyr of energy in the year 2070. The growth in electricity demand was as a result of some forms of economic development coupled with high population demanding power to meet their daily needs.

From observations, the total future energy demands in the business-as-usual scenario was lower than that of the total final demands in the moderate economic growth scenario. The total final energy demand in the moderate economic growth scenario increased from 1.77GWyr of energy in the year 2019 to 14 GWyr of energy in the year 2070. Comparing the BaU scenario with the MEG scenario, the high energy demand in the MEG model can be attributed to stronger economic growth indicators and the penetration of modern energy technologies of the economy. The total final energy demand in the high economic growth scenario indicated that, future electricity demand is projected to peak at 39 GWyr in 2070. The high electricity demand is as a result of robust economic development, massive technology adoption, and widespread integration of policies concerning energy use.

However, several factors may distract the penetration of essential modern energy technologies, making the adoption process very difficult. A critical danger to high electrification development is the availability of key resources for electric power generation technologies, storage batteries, electricity grids, and electricity powered vehicles. The main consumers of electricity are the household and industrial sectors. These two sectors account for over 90 percent of the total electricity consumption of the country. For instance, the high electricity consumption in the residential sectors can be attributed to energy use for cooking, lighting, and appliances.

To meet the growing demand for electricity, it is important to make adequate investments in the electricity sector of the country. A report from Ghana's Energy Commission revealed that, electricity generation of the country nearly quadrupled from 11,200 GWh of electricity in 2011 to 22,051 GWh of electricity in the year 2021, illustrating a yearly average growth rate of 7 percent. This analysis indicates that a total of 75,000 GWh is required to meet the growing demand of 7.8 GWyr of energy in the business-as-usual model. Again, if the country can achieve the gross domestic product growth of 8.8 percent as projected in the SNEP, a total of 350,000 G Wh of electricity would be required to meet the 39 GWyr of energy projected in the high economic growth scenario.

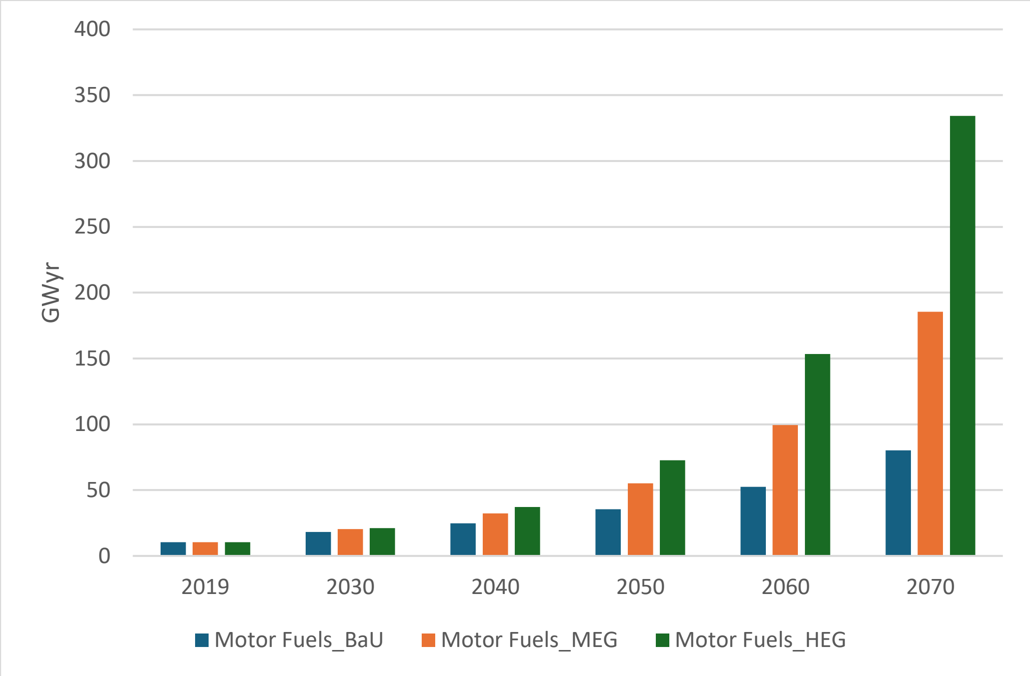

Figure 14: Total Final Motor Fuels Demand Projections in the BaU, MEG, and HEG Scenarios.

Source: Author's Construct (2024)

The results from the analysis also projected the total final energy demand for motor fuel in the business-as-usual, moderate economic growth, and high economic growth scenarios as illustrated in figure 14. The result from the business-as-usual revealed that, in the absence of significant policy changes, there would be a substantial surge in the total final demand for motor fuels driven by high population growth coupled with consistent increase in car ownership and usage. As indicated in the figure above, the total projected demand for motor fuels increased from 10.5 GWyr in 2019 to 80 GWyr in 2070 in the business-as-usual model. Though the business-as-usual model projected a surge in future demand for energy, the level of this surge was not high as the changed observed under the moderate economic growth model. This is because demand for energy in the moderate economic growth model increased from 10.5 GWyr in 2019 to 185 GWyr in the year 2070. This change indicates a higher level of economic activity and moderate policy interventions.

To effectively tackle the increased energy demand, there is the need for the implementation of regulations that advocate for the adoption and use of alternative modern fuels and other measures to ensure efficiency in transportation. However, the expected surge in energy demand was significantly higher in the HEG scenario than that of BaU and MEG scenarios. Specifically, the total final energy demand for motor fuels increased significantly in the high economic growth scenario from 10.5 GWyr in 2019 to 334 GWyr in 2070. This demonstrates the potential burden on energy resources and the environment. The HEG scenario highlights the significance of allocating resources towards alternate transport fuels, technology, and infrastructure to effectively address future demands in a sustainable manner.

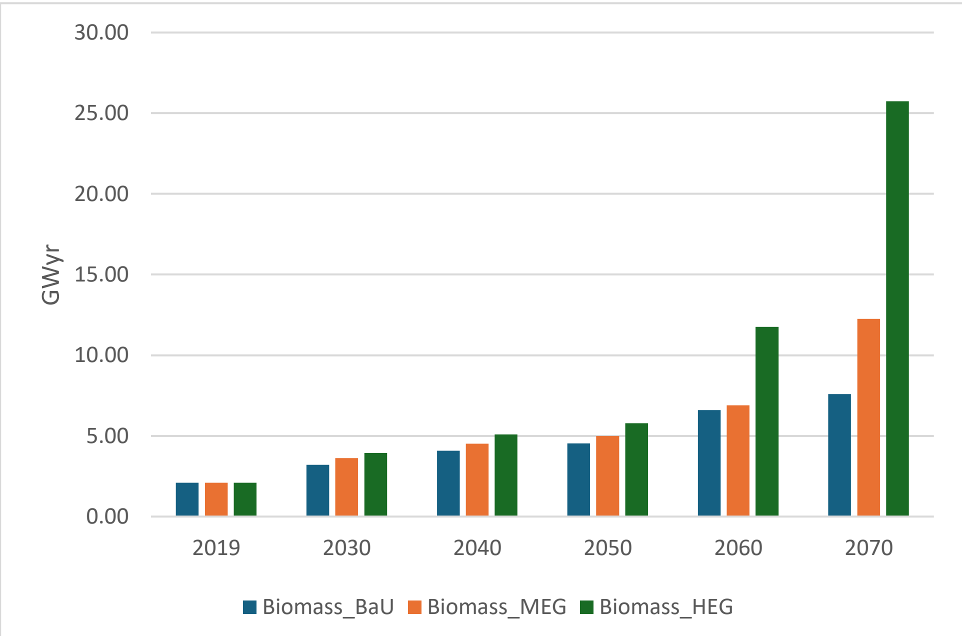

Figure 15: Total Final Modern Biomass Demand Projections in the BaU, MEG, and HEG Scenarios

Source: Author's Construct (2024)

Figure 15 depicts the projections for the total final demand for modern biomass in the Business-as-Usual, Moderate Economic Growth and High Economic

Growth scenarios. From the diagram, the demand for biomass steadily increases in the Business-as-Usual scenario where demand was projected to rise from 2.1 GWyr in 2019 to 7.6 GWyr in 2070. The steadily growth in demand was due to no substantial change in energy penetration, GDP growth rate, and no policy change in the economy. There was a moderate increase in GDP growth rate, policy support for the adoption of modern ES in the Moderate Economic Growth scenario. Also, there was a high projection for the demand for modern biomass in the High Economic Growth scenario than that of moderate economic scenario. The sharp increase in demand from 2.1 GWyr in 2019 to 25 GWyr in 2070 indicates the importance of higher policy support for modern ES and technologies to ensure sustainable energy use in the future. Again, the higher GDP growth rate led to higher income levels of citizens, urbanisation, and greater penetration of modern technologies.

Table 5: Final Energy Per Capita in the BaU, MEG, and HEG Scenarios

Years	FE per Capita (MWh/cap)_BaU	FE per Capita (MWh/cap)_MEG	FE per Capita (MWh/cap)_HEG
2019	4.04	4.04	4.04
2030	5.40	6.02	6.41
2040	6.00	7.70	9.37
2050	6.95	10.60	15.07
2060	8.33	15.40	26.18
2070	10.27	23.15	46.76

Source: Author's Construct (2024)

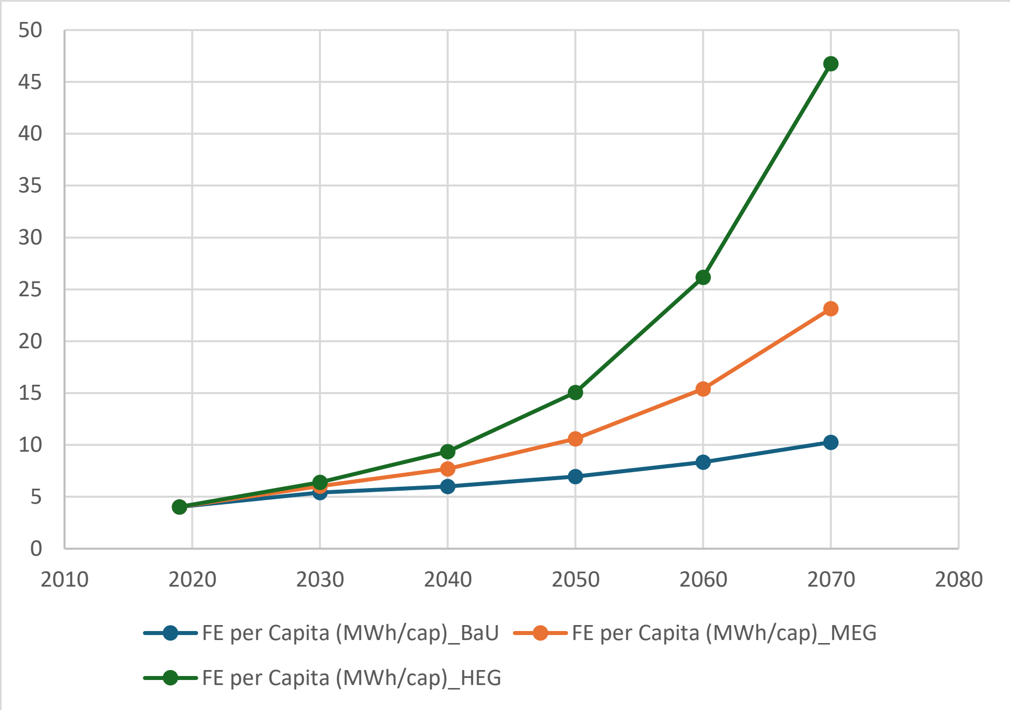

Figure 16: Final Energy Per Capita in the BaU, MEG, and HEG Scenarios
Source: Author's Construct (2024)

Figure 16 depicts the final energy per capita in the Business-as-Usual, Moderate Economic Growth and High Economic Growth scenarios. From the illustrations, energy consumption per capita increases in all levels. However, the differences are not the same across different scenarios as indicated in the diagram. Specifically, final energy consumption per capita in the Business-as-Usual scenario increases from 4.04 MWh/cap in 2019 to 10.27 MWh/cap in 2070. This growth is because of a steady improvement in living standards and economic conditions of the people, leading to higher energy consumption per person.

In the Moderate Economic Growth scenario, energy consumption per capita was projected to increase from 4.04 MWh/cap to 23 MWh/cap by 2070. This scenario assumed a 6.3 percent growth rate in GDP and improved living standards, leading to higher energy consumption per person. The increase in more pronounced than in the BaU scenario due to more dynamic economic activities and greater access to ES. The High Economic Growth scenario shows the most significant increase in energy consumption per capita, reaching 46.76 MWh/cap by 2070. This scenario assumes a GDP growth rate of 8.3 percent in 2030 and reaching 8.8 percent by the end of 2050. This will lead to improvement in living standards and higher energy use per person. This also means that households and businesses will start using higher energy intensive appliances, electricity fuelled vehicles, and other ES.

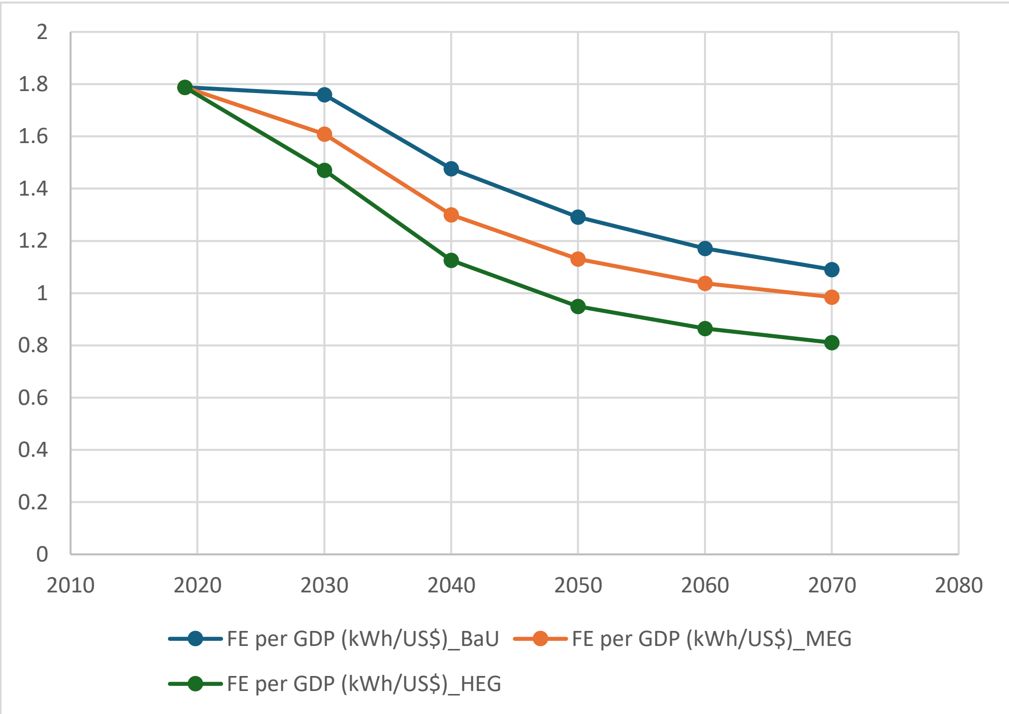

Figure 17: Final Energy Per GDP in the BaU, MEG, and HEG Scenarios
Source: Author's Construct (2024)

Figure 17 illustrates the final energy per GDP in the Business-as-Usual, High Economic Growth, and Moderate Economic Growth scenarios. Interestingly, the diagram shows a downward trend in the energy per GDP of the economy, indicating a lower energy intensity in future. To be precise, energy intensity or energy consumption per GDP in the Business-as-Usual scenario decreases from 1.79 kWh/US$ in 2019 to 1.09 kWh/US$ in 2070. This decline is because of gradual improvements in energy efficiency and economic productivity. Again, energy consumption per GDP decreases to 0.98 kWh/US$ by 2070 in the Moderate Economic Growth scenario. This scenario assumes moderate economic growth and significant improvements in energy efficiency and technologies. Due to the robust policy support for energy efficiency measures, the decline is more pronounced in the MEG than in the business-as-usual model. Notwithstanding, the Higher Economic Growth scenario shows a higher decline in energy intensity from 1.79 kWh/US$ in 2019 to 0.81 kWh/US$ in 2070. This is as a result of the improvement in energy efficiency in the HEG scenario, especially through the introduction of electricity fuelled vehicles and electric cooking stoves in the economy. Again, it is worth noting that an increase in projected energy demands in the various scenarios did not cause energy intensity to go up due to the introduction of advanced technologies in the economy.

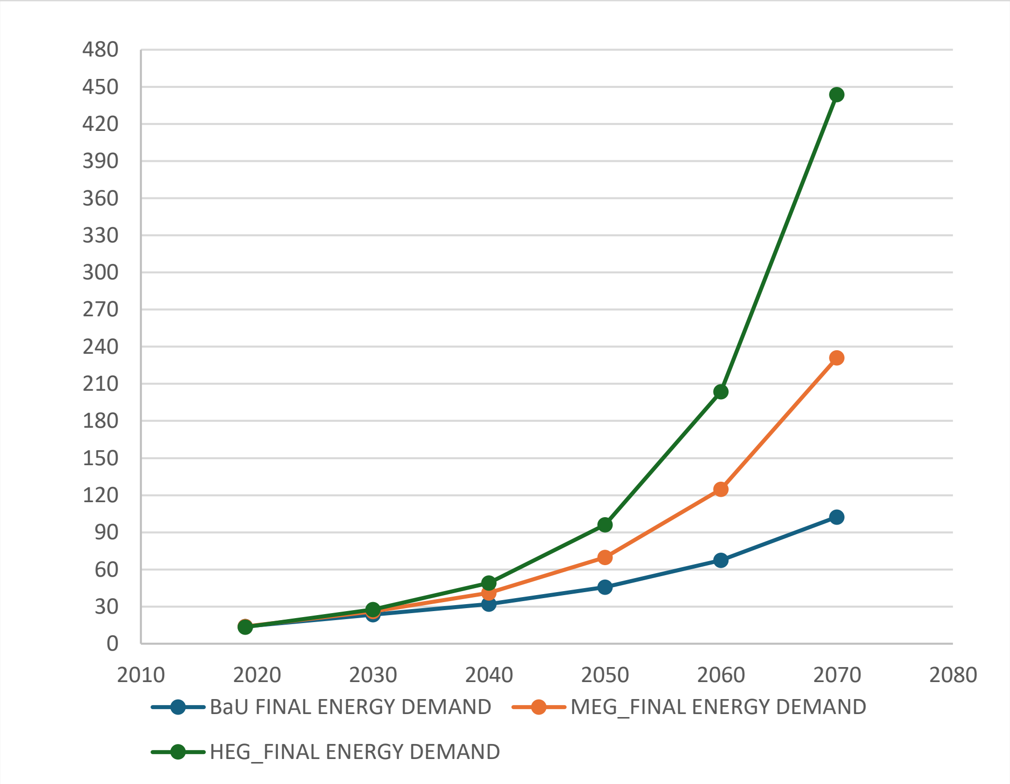

Figure 18: Total Final Energy Demand (2019 - 2070)

Source: Author's Construct (2024)

From Figure 18, the study spans from 2019 to 2070 and examines three distinct scenarios: Business-as-Usual (BaU), Moderate Economic Growth (MEG), and

High Economic Growth (HEG). Each scenario reflects different socio-economic trajectories and policies implementations, providing a robust framework for understanding future energy demands. The BaU scenario, as previously mentioned, depicts a continuation of current patterns without substantial improvements in energy efficiency or the implementation of new regulations.

In 2019, the final energy amounted to 13.65 gigawatt-years, which is equivalent to 10,032 kilotonnes of oil equivalent (ktoe). By the year 2030, the demand for energy is projected to reach 23.48 GWyr, signifying a substantial increase fuelled by both economic expansion and population growth. The trend of increasing energy consumption persists, with a projected value of 67.53 GWyr in 2060 and a peak of 102.44 GWyr in 2070. The consistent increase in energy consumption in this scenario is propelled by a population growth rate of 2.1 percent and a GDP growth rate of 5 percent. These figures indicate that existing patterns will persist without substantial improvements in energy efficiency or the implementation of new energy policies in the country.

In the MEG scenario, the energy consumption increases from 13.65 GWyr in 2019 to 26.14 GWyr by 2030, starting from the same base year as the BaU scenario. The MEG scenario, which considers moderate economic development and the adoption of efficient energy technology, resulted in a somewhat greater increase in final energy demand compared to the BaU scenario, as seen in the figure. The trend persists as the economy's ultimate energy demand is projected to increase to 69.80GWyr in 2050, 124.81GWyr in 2060, and reach its highest point at 230.9GWyr in 2070. The increase in the ultimate energy demand for the MEG can be attributed to a 6.3 percent growth in GDP from 2030 to 2070 and the implementation of energy-efficient technology, including the integration of electric vehicles into the economy.

The HEG scenario was based on the assumption of a robust economic growth and substantial enhancements in energy efficiency. Due to the use of identical data in the formulation of the base year, the 2019 final energy demand did not deviate from the BaU and MEG scenarios. Nevertheless, the overall energy demand increased to 96GWyr, 203GWyr, and reached its highest point at 443GWyr in the years 2050, 2060, and 2070, respectively. The HEG scenario portrays the greatest energy requirement compared to the other two scenarios. This is due to an 8.8% increase in GDP and widespread implementation of advanced energy technologies, such as the use of LPG for cooking by 50% of urban households in 2050 and the introduction of electric vehicles. This suggests that future energy consumption is substantially influenced by economic growth, beneficial government policies, and the introduction of energy-efficient technologies.

Discussion of Results

This part discusses the findings of the study based on the specific objectives:

1. Effects of different penetration scenarios on final energy demand of Ghana.
2. Patterns of energy consumption per capita of Ghana under different penetration scenarios.
3. Patterns of energy intensity under different penetration scenarios of Ghana.

Effects of Different Penetration Scenarios on Final Energy Demand in Ghana

The first research objective was intended to find out the effect of different penetration scenarios on final energy demand, as indicated in figure 18. From figure 18, the findings from the study showed a significant increase in energy demand across various sectors under all three scenarios (Business-as-Usual, Moderate Economic Growth, and High Economic Growth). Comparing the BaU to HEG scenario, the higher energy demand projections in the HEG scenario were fuelled by an 8.8% GDP growth rate**,** the introduction of electricity-fuelled vehicle, 50 percent increase in the consumption of LPG for cooking, and an increase in the urban population share to 85 percent. The steady growth in population growth at 2.0 percent post-2030 by the HEG signifies that higher economic growth can lead to higher energy demand because of more efficient use of resources.

Again, taking the moderate economic growth scenario into consideration, energy demand was projected to reach 230.94 GWyr in 2070. This scenario strikes a balance between the business-as-usual and high economic growth scenarios, with a GDP growth rate of 6.3 percent and similar urbanisation trends as the BaU scenario. Though energy demand was not as high as the HEG scenario, it was clearly above the BaU scenario due to the introduction of other favourable energy demand policies, like the introduction of electricity fuelled vehicles in the economy.

From the projections, the steady increase in energy demand from 13.65 GWyr in 2019 to 102 GWyr in 2070 in the BaU scenario aligns with findings from various studies on energy demand in developing countries. For instance, the International Energy Agency (IEA), revealed similar trends in countries with rapid population growth and economic development but without significant policy changes or technological advancements (IEA, 2018). The BaU scenario's steady increase in energy demand aligns with the IEA's projections for sub-Saharan Africa, which anticipates a steady rise in energy demand due to urbanisation and economic growth, despite limited improvements in energy efficiency.

However, the BaU findings also resonate with the concerns raised by Ouedraogo (2017), who argues that relying on existing trends without any substantial policy interventions can lead to unsustainable energy consumption patterns. Based on the existing capacity as a country, with a current energy supply of 12,371 ktoe (Energy Commission, 2022), over 76,753 ktoe of energy would be needed to meet the business-as-usual projection of 102 GWyr in 2070.

Assuming that the country is able to meet the moderate economic growth GDP growth of 6.9 percent, 173,943 kilotons of oil equivalent energy would be required to meet the MEG projection of 230 GWyr in 2070. This necessitates that some form of investment be pulled into Ghana's energy sector. Furthermore, the MEG scenario supports Mensah et al.'s (2021) arguments, which revealed that energy demand in developing countries is highly sensitive to energy efficiencies. Their analysis highlighted that moderate economic growth could lead to significant increases in consumption, particularly in urban areas where energy-intensive activities are concentrated.

The HEG scenario, which projected a dramatic increase in energy demand to 443 GWyr by 2070, emphasises the profound impact of rapid economic growth and significant improvements in energy efficiency. The analysis of the HEG scenario aligns with the work of Sefa Nyarko (2024), who argued that the government's business-as-usual posture cannot achieve the national energy transition targets. With this, massive investment is needed to boost the current energy supply in Ghana. For example, if the projected demand is 443 GWyr in 2070, the energy supply should amount to 333,579 ktoe in that same year to balance the demand requirement. This is also supported by the findings of Ahenkan et al. (2021) on energy, which suggested that high economic growth, urbanisation, and industrialisation in developing countries can lead to exponential increases in energy demand. The scale of economic activities can offset energy efficiency gains, highlighting the complex relationship between urbanisation and energy demand.

These scenarios projection emphasize the need for comprehensive policy measures to effectively address energy demand issues in the country. The growing demand for energy means that Ghana must diversify its energy sources, focussing on RE technologies such as solar, wind, and biomass. Expanding RE capacity will not only help meet demand but also contribute to energy sustainability. Though energy efficiency is not sufficient to tackle the rising demand for energy because of the issue of the rebound effect, it is essential to improve energy efficiency across all sectors to manage the rise in consumption. To effectively optimise energy use and ensure efficient resource utilisation, governments and other major stakeholders should enact policies that promote the use of energy-efficient appliances, industrial processes, and transportation to reduce energy consumption significantly. Additionally, the growing demand for energy calls for the implementation of smart grid technologies and demand-side management to optimise energy distribution and minimise waste.

Notwithstanding, the higher demand for energy in the projections also raises energy security issues and environmental concerns in the country. The higher demand calls for diversification of energy sources and a reduction in dependence on energy imports to enhance the country's energy security. The country's ability to rely on a diverse mix of energy sources, including renewables, natural gas, and hydroelectric power, will help to mitigate geopolitical risks and price volatility. Since consumers are going to demand more power in the coming years, there should be an upgrade and expansion in energy infrastructure to withstand disruptions in the energy system.

Apart from energy security issues, the significant increase in energy demand has profound environmental implications, particularly GHG emissions and resource depletion. Without substantial shifts towards RE and energy efficiency, the business-as-usual and moderate economic growth scenarios could lead to significant increases in emissions. Also, the high economic growth scenario, while promoting economic growth, poses the highest risk for environmental degradation unless paired with robust sustainability measures. This means that, there is a need to adopt sustainable energy practices, such as increasing the share of renewables in the energy mix and promoting energy efficiency technologies, to mitigate environmental impacts and meet consumers' demand.

The findings align with the broader literature, which indicates that socio-economic indicators, access to modern energy appliances, and urbanisation are primary drivers of energy consumption. In 2019, the Energy Commission of Ghana report on the Strategic National Energy Plan (SNEP), supports these projections, indicating that moderate economic growth can still lead to significant increases in energy demand, especially if accompanied by technological advancements and policy support. The findings are also consistent with global trends observed in developing countries, where penetration of modern appliances, economic growth, and urbanisation drive energy demand (IEA, 2018).

The projections for long-term demand align with Fujii et al. (2019) who indicated the need to keep pace with the development trend and sectoral economic growth to meet the growing demand for energy. Also, the study's BaU scenario reflects Ouedraogo's (2017) analysis of Africa's energy future under the reference scenario, which states that the energy demand in 2040 will be three times that of 2015, with a corresponding increase in GHG emissions. However, the findings from the study contradict the work of Botwe-Ohenewaa et al. (2022), which indicated that implementing energy efficiency measures will reduce energy consumption in the economy.

Patterns of Energy Per Capita under Different Penetration Scenarios.

The second research objective was to analyse the effect of different penetration scenarios on final energy consumption per capita, as indicated in figure 16 above. This is to compare the total amount of energy that would be consumed per person under different penetration scenarios. The results of the study illustrated varying levels of penetration of technologies such as LPG for cooking, electricity-fuelled vehicles, and efficient household appliances. The study projected a slower penetration rate for modern energy technologies in the business-as-usual model. From the result, final energy consumption per capita in the Business-as-Usual scenario increases from 4.04 MWh/cap in 2019 to 10.27 MWh/cap in 2070 while final energy consumption per capita is projected to increase from 4.04 MWh/cap to 23 MWh/cap by 2070 in Moderate Economic Growth scenario.

The changes in energy per capita between the two were a result of the penetration of energy-efficient technologies, such as the introduction of electricity-fuelled vehicles in the MEG scenario. The High Economic Growth scenario shows the most significant increase in energy consumption per capita, reaching 46.76 MWh/cap by 2070. Apart from the increase in urbanisation rate, the HEG scenario also saw a higher penetration of modern ES and technologies, such as the 50 percent adoption of LPG for cooking and the introduction of electricity-fuelled vehicles in the economy. The study's findings align with the observations made by Ponce et al. (2019), which indicate that urbanisation significantly influences per capita energy consumption.

However, the impact of urbanisation on energy consumption varies across different socioeconomic levels. This discovery presents a novel approach to managing the excessive rise in energy consumption. This emphasises the potential effect of factors such as energy efficiency, technology penetration, economic growth, and behavioural changes when analysing energy demand. That is, an individual may choose to adopt new attitudes that increase his energy use, such as longer use of electrical appliances and overreliance on energy intensive activities. Again, when making an energy consumption per capita analysis, it is important to look at the rate at which individuals adopt new technologies. Rapid adoption of energy-efficient technologies leads to higher energy use as more households and industries get access to modern ES. This phenomenon is similar to the concept of the energy efficiency hypothesis, which highlights that as consumers transition from traditional to modern energy sources, their overall energy consumption increases due to the higher efficiency and convenience of modern technologies.

Interestingly, the results from the study indicated that the penetration of energy-efficient technology did not reduce energy consumption per capita, rather, there was a significant increase in energy per capita across all scenarios. These findings from the study necessitate paying attention to the mechanism known as the ‘energy efficiency paradox’ because none of the scenarios indicated a reduction in energy per capita consumption. Under different scenarios, the projected energy consumption per capita trends have significant implications for Ghana’s energy security and sustainability. For instance, the high increase in energy consumption per capita may put pressure on infrastructure and energy resources. This is coherent with Goldthau et al. (2020), which emphasizes the possibility of the risks of rapid energy demand on energy security. Again, this is in line with Gillingham et al. (2016), who opined that while energy efficiency measures are widely recognised as cost-effective and environmentally beneficial, their potential to stimulate additional energy consumption complicates policy decision-making.

The current energy supply of 12,331 kilotonnes of oil equivalent (ktoe) indicates a robust system capable of meeting the current energy demand. However, the projected future per capita demands of the economy necessitate the need for significant expansion and diversification of the energy supply to prevent shortages in the future. The heavy reliance on biomass and oil, despite their declining shares, suggests that Ghana must diversify its energy sources. Increasing the share of renewables like solar and wind could help mitigate future supply risks and address any demand and environmental concerns. This is in line with Dupon, Germain, and Jeanmart's (2021) revelation that achieving a complete global energy transition within the current business-as-usual framework is not possible until the end of the century. They assert that a full transition may be accomplished by 2070, provided that energy consumption is maintained at its current level.

This necessitates the need to pay attention to energy security and sustainability in the economy because the adoption of energy-efficient technologies alone may not be sufficient to achieve meaningful reductions in energy consumption and environmental impacts, as clearly stated in the literature (Brockway et al., 2021; Sorrel, Gatersleben, & Druckman, 2020). Empirical findings suggest the need for policymakers to consider a range of factors, including consumer behavioural responses, market dynamics, the rebound effect, and technological innovation, when designing energy efficiency policies and strategies to mitigate consumption (Sorrel, Gatersleben, & Druckman, 2020).

Patterns of Energy Intensity under Different Penetration Scenarios in Ghana

The third research objective was intended to analyse the energy intensity patterns under different penetration scenarios, as indicated in figure 17 above. The purpose of this analysis is to understand how the economy can efficiently utilize its energy to generate economic output. This analysis aims to better understand how our country uses its energy resources. The study of the energy demand of a country provides several opportunities to reduce energy intensity, and the most understood is energy efficiency. Being efficient with energy means we need less of it, which means we optimise the existing processes in order not to create as many RE projects in an attempt to achieve net zero emissions.

As illustrated in figure 17, under the Business-as-Usual scenario, where the various socio-economic indicators assumed little or no change in policies, energy intensity decreased from 1.79 kWh/US$ in 2019 to 1.09 kWh/US$ in 2070. Empirical findings on energy intensity and energy efficiency support this result, as developing countries typically exhibit a steady increase in energy intensity over time due to small improvements in policy interventions (Bilgili & Ozturk, 2015; Aboagye, 2017). The explanation for this is that the gradual adoption suggests the need for improvements in energy efficiency over the fifty-year period.

However, the relatively slow rate of decrease in energy intensities indicates that while there are improvements in measures, they are not aggressive enough to reduce intensities drastically compared to other scenarios. Comparatively, the Moderate Economic Growth scenario projected slightly different results, with energy intensity dropping from 1.79 kWh/US$ in 2019 to 0.98 kWh/US$ by 2070. The slight changes in energy intensities in the MEG were the result of growth in GDP from 5 percent to 6.9 percent and the penetration of efficient energy technologies. Also, the High Economic Growth scenario recorded a substantial decline in energy intensity, from 1.79 kWh/US$ in 2019 to a record of 0.81 kWh/US$ in 2070. This scenario assumed a high economic growth indicator, with GDP reaching 8.3% in 2030 and peaking at 8.8% in 2040. But the share of urban population remained at 56% until 2030 and increased at an average of 10% every 10 years until 2070.

Again, this scenario also assumed penetration of efficient modern ES, like the introduction of electric-fuelled vehicles and LPG for cooking, where 50% of urban households would be using LPG for cooking by 2050, as projected in the National Energy Transition Framework (2022).

Interestingly, the results indicated a downward trend in the energy per GDP of the economy, indicating a lower energy intensity across different scenarios in the future. Growth in socio-economic indicators and technological advancements in energy use primarily drive this trend. As the economy continues to increase its GDP through urbanisation and the adoption and integration of more efficient technologies in various sectors such as industrial, transportation, and household, energy consumption per unit of GDP will decrease. The study clearly indicated that the introduction of innovations such as electricity-fuelled vehicles, energy-efficient appliances, and advanced industrial processes significantly reduced the amount of energy required for economic activities.

The result indicated a clear variation among the energy intensities under the three scenarios. The level of policy support for growth in socio-economic indicators and energy efficiency measures can account for this variation. For instance, in the HEG scenario, where there was an improvement in economic growth and the implementation of energy efficiency measures, the impact on energy intensity was more pronounced. Apart from the massive growth in the socio-economic indicators, the results also reflect an improvement in energy management practices. Typically, growth in the economy will push industries and businesses to adopt best practices in energy management, by optimising their energy use to reduce costs and improve competitiveness. Retrofitting old equipment, conducting energy audits, and implementing energy management systems all contribute to lower energy intensities.

The findings align with the research conducted by Mahmood & Ahmad (2018) and Chen et al. (2018), which emphasize a notable decrease in energy intensity as a response to economic growth in developed nations. The only explanation for this is that developed nations succeeded in energy efficiency not only via their economic advancement but also as a result of steady or decreasing populations. In Ghana, the results from the HEG scenario demonstrate the importance of reducing population growth rates to maintain a stable population while improving energy efficiency. The outcomes of the study align with the studies undertaken by Diaz et al. (2019), which suggest that the connection between economic growth and energy consumption is complex. This relationship is influenced by institutional and policy frameworks, technological advancements, and the sectoral makeup of an economy. The study observed that the massive decline in energy intensities in the high economic growth scenario was not solely due to growth in socio-economic indicators. The HEG scenario saw the introduction of government policies such as a 50% increase in the use of LPG and the introduction of electricity-fuelled vehicles to improve energy efficiency.

Chapter Summary

In this chapter, the researcher presented the descriptive analysis, the patterns of energy supply in the economy, followed by the results of the study and their discussions. From the descriptive analysis, the study depicted an overall increase in the population, gross domestic product and gross domestic product per capita of the economy from the years 2019 to 2070. The man results projected the total final future energy demand of the economy. Specifically, the results projected the total final future energy demand of the sectors, final demand based on fuel types, future total final energy consumption per capita, final energy consumption per GDP, and the overall total final energy demand based on different penetration scenarios.

The first objective sought to compare the effects of different penetration scenarios on the final energy demand of the economy from 2019 to 2070. The results showed an increase in overall energy demand across different penetration scenarios. The second research objective sought to examine the patterns of energy consumption per capita across different penetration scenarios. From the results, the researcher concluded that while penetration of modern energy efficient technologies are good and more efficient, their adoption can lead to an overall increased in energy consumption per capita. The third objective was to assess how different penetration scenarios affect energy consumption per GDP of the economy. The results showed a downward trend in energy consumption per GDP of the economy, indicating a lower energy intensity across different penetration scenarios.

CHAPTER FIVE

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Overview

This chapter provides an overview of the research methodology, and the results obtained from studying the effects of adopting modern ES and technology on the overall energy demand of Ghana. The major findings are used to draw conclusions, which in turn inform appropriate recommendations and identify areas for additional investigation. The first part provides an overview of the research procedure, while the subsequent section provides a concise summary of the principal discoveries of the study.

Summary of the Research Process

Simulation analysis was conducted to examine the effect of modelling the adoption of modern ES and technologies on final energy demand in Ghana. The following research questions guided the study:

1. What is the effect of different penetration scenarios on final energy demand in Ghana from 2019 to 2070?
2. How does the penetration of different adoption scenarios affect the final energy consumption per capita in Ghana?
3. How does the penetration of different adoption scenarios influence energy intensity patterns in Ghana?

The study utilised a quantitative research procedure, specifically employing a cross-sectional research design. The researcher's decision to use this design allowed them to collect data at a certain moment, capturing a precise representation of the current energy consumption and the factors that affect demand in Ghana. The International Atomic Energy Agency model (MAED-2) was utilised to examine different possibilities for the growth of the energy sector and predict forthcoming energy requirements. The study's sectoral segment was divided into four primary sectors: industrial, transport, service, and home. The sector was subdivided into various subsectors. The industry subsector included agriculture, construction, mining, and manufacturing. The transportation subsector encompassed freight, urban, and intercity transportation. The household's subsector was divided into urban and rural categories. The model accounted for factors such as, government policies, GDP growth rate, household size, urban population, population growth, technological advancements, and market penetration of new energy technologies. Based on these factors, the study analysed the future demand for energy in Ghana under three scenarios: Business-as-Usual (BaU), Moderate Economic Growth (MEG), and High Economic Growth (HEG) scenarios.

Summary of Key Findings

The findings indicate that the High Economic Growth scenario showed the highest increase in energy demand, followed by the Moderate Economic Growth and Business-as-Usual scenarios. The significant increase in energy demand was driven by factors such as population growth, urbanisation, efficient energy penetration, and economic development. The study also examined the patterns of energy consumption per capita in Ghana under different penetration scenarios. The study revealed that while penetration of modern energy technologies is more efficient, their adoption can lead to an increased in overall energy consumption and energy per capita due to greater convenience and higher usage rates.

The study confirmed the presence of rebound effect in the results. That is, the study showed that the introduction of energy efficiency technologies did not reduce the demand for energy, rather, there was a significant increase in demand across all scenarios. Thus, the adoption of modern ES was found to improve energy access and reduce energy poverty but required substantial investments in infrastructure and technology to meet growing demand. The last objective of the study examined the patterns of energy intensity under different penetration scenarios.

The findings from the study revealed a downward trend in the energy per GDP of the country, indicating a lower energy intensity across different scenarios in the future. From the results, as the economy continues to increase its urbanisation rate, adopt and integrate more efficient technologies in various sectors such as industrial, transportation, and household, energy consumption per unit of GDP will decreases. Lastly, the study clearly indicated that an introduction of innovations such as electricity fuelled vehicles, Energy-efficient appliances, and advanced industrial processes significantly reduce the amount of energy required for economic activities.

Conclusions

The findings of the study have implications for Ghana’s future energy consumption patterns. Firstly, due to the adoption of modern ES and socio-economic factors such as GDP, population growth, urbanisation, and household size, Ghana’s future energy demand will significantly increase across all scenarios. For instance, the Business-as-Usual scenario with its steady rise in energy demand, still emphasizes the importance of policy interventions to prevent unsustainable energy consumption patterns.

Also, the introduction of efficient energy technologies, GDP growth, and energy efficiency measures will increase energy access and significantly reduce energy intensity in the country. These underline the need for robust energy policies and investments to manage the exponential increase in energy consumption due to the higher energy access and mitigate potential energy security risks. The results from the study align with broader literature on the complex relationship between modern energy technologies and energy demand, where efficiency gains must be complemented by comprehensive policies to manage overall energy demand effectively.

The study confirmed that without robust policies, the transition to modern energy technologies will be slow, resulting in minimal adoption of technologies like electricity-fuelled vehicles. Thus, moderate policy support can achieve significant impacts on energy technology adoption, but stronger policies are needed to accelerate the adoption of technologies and improve energy efficiency significantly. The implications of different energy adoption scenarios highlight the need for a diversified energy mix and substantial policy measures to ensure energy security and sustainability. In all, the transition to modern ES and technologies is feasible and offers substantial benefits for Ghana's energy security, economic development, and environmental sustainability.

Recommendations

Considering the findings and conclusions of the study, the following recommendations are suggested.

Firstly, the study highlights the relevance of robust and consistent policy support to accelerate the adoption of modern energy technologies. Hence, policy makers should enhance existing policies and introduce new regulatory frameworks that promote RE and energy efficiency. These policies should include incentives for investments in clean energy technologies, subsidies for RE projects, and stringent regulations on energy efficiency standards.

Secondly, the study recommends that, though energy efficiency measures are necessary and crucial for reducing overall energy demand and minimising environmental impacts, it must be complemented with attitudinal change to prevent the rebound effect.

Thirdly, the study recommends the implementation of nationwide energy efficiency programs targeting various sectors, including household or residential, commercial, industrial, and transportation sectors. These programs should promote the use of energy-efficient appliances, encourage behavioural changes towards energy conservation, and support the retrofitting of existing buildings to improve energy performance in the various sectors of the economy. Also, the findings from the study make it necessary to recognise the importance of public awareness and education campaigns to foster the adoption of modern energy technologies and practices. As a results, the government and other relevant stakeholders should engage in outreach activities to educate the public about the benefits of using RE and Energy-efficient technologies. These educational programs should be integrated into school curricula, and awareness campaigns should utilize various media platforms to reach a broad audience.

Finally, monitoring and evaluation matters anytime you want to ensure success in energy policies and programs. Therefore, the government should establish mechanisms for regularly assessing the impact of energy initiatives, tracking progress towards targets, and making necessary adjustments to strategies and policies based on empirical evidence.

Suggestions for Further Studies

The study focused on modelling how the adoption of modern energy services and technologies affect energy demand. Further studies are encouraged to model the future energy supply patterns of Ghana using disaggregate data. Secondly, understanding the behavioural aspects of energy consumption and the factors influencing consumer decisions regarding energy use and technology adoption is important. Therefore, further studies should also focus on consumer behaviour, preferences, and willingness to adopt new technologies to help in designing effective policies and programs to reduce energy demand.

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APPENDICES

APPENDIX A

Appendix A: Showing Industry Sector Useful Energy in the Business-as-Usual Model

2.1. INDUSTRY - Useful Energy						
2.1.1. Useful energy demand for Motive Power [GWyr]	**2019**	**2030**	**2040**	**2050**	**2060**	**2070**
Agriculture	**0.00856**	**0.014635**	**0.02384**	**0.038832**	**0.063254**	**0.103033**
Agriculture	0.00856	0.014635	0.02384	0.038832	0.063254	0.103033
Construction	**0.011189**	**0.019137**	**0.031172**	**0.050776**	**0.082709**	**0.134725**
Construction	0.011189	0.019137	0.031172	0.050776	0.082709	0.134725
Mining	**0.020549**	**0.023431**	**0.038166**	**0.062169**	**0.101267**	**0.164953**
Mining	0.020549	0.023431	0.038166	0.062169	0.101267	0.164953
Manufacturing	**0.048402**	**0.082791**	**0.134857**	**0.219668**	**0.357816**	**0.582845**
Manufacturing	0.048402	0.082791	0.134857	0.219668	0.357816	0.582845

2.1.2. Useful energy demand for Electricity specific uses [GWyr]	**2019**	**2030**	**2040**	**2050**	**2060**	**2070**
Agriculture	**0.020088**	**0.034358**	**0.055965**	**0.091161**	**0.148491**	**0.241877**
Agriculture	0.020088	0.034358	0.055965	0.091161	0.148491	0.241877
Construction	**0.028544**	**0.04882**	**0.079523**	**0.129535**	**0.210999**	**0.343695**
Construction	0.028544	0.04882	0.079523	0.129535	0.210999	0.343695

Mining	**0.023974**	**0.04686**	**0.076329**	**0.124333**	**0.202525**	**0.329891**
Mining	0.023974	0.04686	0.076329	0.124333	0.202525	0.329891
Manufacturing	**0.106165**	**0.019532**	**0.031816**	**0.051824**	**0.084416**	**0.137505**
Manufacturing	0.106165	0.019532	0.031816	0.051824	0.084416	0.137505

2.1.3. Useful energy demand for Thermal uses [GWyr]	2019	2030	2040	2050	2060	2070
Agriculture	**0.065401**	**0.111857**	**0.182204**	**0.296791**	**0.483441**	**0.787474**
Agriculture	0.065401	0.111857	0.182204	0.296791	0.483441	0.787474
Construction	**0.048616**	**0.079631**	**0.12971**	**0.211285**	**0.34416**	**0.560601**
Construction	0.048616	0.079631	0.12971	0.211285	0.34416	0.560601
Mining	**0.085291**	**0.145876**	**0.237617**	**0.387054**	**0.630469**	**1.026968**
Mining	0.085291	0.145876	0.237617	0.387054	0.630469	1.026968
Manufacturing	**0.140133**	**0.140296**	**0.228527**	**0.372246**	**0.60635**	**0.98768**
Manufacturing	0.140133	0.140296	0.228527	0.372246	0.60635	0.98768

Source: Author’s construct (2024)

Appendix B: Showing Services Sector Useful Energy in the Moderate Economic Growth Model

5. SERVICES						
5.1. Useful Energy Demand in Service Sector [GWyr]	**2019**	**2030**	**2040**	**2050**	**2060**	**2070**
Useful energy demand for Space heating & air conditioning						
Total area heated (Million m2)	0	0	0	0	0	0
Space heating	0	0	0	0	0	0
Air conditioning	0.280266288	0.399753161	0.492095425	0.605768586	0.745700044	0.917955418
Useful energy demand for Motive Power						
Service(Motive Power)	0.294579726	0.613702103	1.196009594	2.33083599	4.542435481	8.852497638
Useful energy demand for Electricity Specific Uses						
Service(Electricity Specific Uses)	0.110467397	0.230138288	0.448503598	0.874063496	1.703413305	3.319686614
Useful energy demand for Thermal Uses						
Service(Thermal Uses)	0.368224658	0.767127628	1.495011992	2.913544988	5.678044351	11.06562205
Total Useful energy demand						
Service						
Motive Power	0.294579726	0.613702103	1.196009594	2.33083599	4.542435481	8.852497638
Electricity Specific Uses	0.110467397	0.230138288	0.448503598	0.874063496	1.703413305	3.319686614
Thermal Uses	0.368224658	0.767127628	1.495011992	2.913544988	5.678044351	11.06562205
Total	**1.053538068**	**2.01072118**	**3.631620608**	**6.724213061**	**12.66959318**	**24.15576172**

Total Useful energy demand						
Space Heating	0	0	0	0	0	0
Motive Power	0.294579726	0.613702103	1.196009594	2.33083599	4.542435481	8.852497638
Electricity Specific Uses	0.110467397	0.230138288	0.448503598	0.874063496	1.703413305	3.319686614
Thermal Uses	0.368224658	0.767127628	1.495011992	2.913544988	5.678044351	11.06562205
Air Conditioning	0.280266288	0.399753161	0.492095425	0.605768586	0.745700044	0.917955418
Total	**1.053538068**	**2.01072118**	**3.631620608**	**6.724213061**	**12.66959318**	**24.15576172**

Source: Author’s construct (2024)

Appendix C: Showing Urban Household Sector Useful Energy in the High Economic Growth Model

4.2. Useful Energy Demand in Household Sector [GWyr]	2019	2030	2040	2050	2060	2070
URBAN						
Apartment						
Space Heating	0	0	0	0	0	0
Water Heating	0	0	0	0	0	0
Cooking	0.674909247	0.848259127	1.136311426	1.523673016	2.043083795	2.739571886
Air Conditioning	0.187671233	0.235874433	0.315972803	0.423685992	0.568117946	0.761789583
Appliances	0.105022831	0.131997858	0.176821763	0.237099217	0.317924884	0.426305606
Electricity - Lighting	0.059360731	0.074607485	0.099942736	0.134012601	0.179696674	0.240955343
Fossil Fuels - Lighting	0.01369863	0.017217112	0.023063708	0.030925985	0.041468463	0.055605079
Family house						
Space Heating	0	0	0	0	0	0
Water Heating	0	0	0	0	0	0
Cooking	0.207664384	0.261002808	0.349634285	0.468822467	0.628641168	0.842945196
Air Conditioning	0.042694064	0.053659999	0.071881891	0.096385986	0.129243377	0.173302496

Appliances	0.070776256	0.088955078	0.119162493	0.159784255	0.214253727	0.287292908
Electricity - Lighting	0.04109589	0.051651336	0.069191125	0.092777954	0.12440539	0.166815237
Fossil Fuels - Lighting	0.009703196	0.012195454	0.016336793	0.021905906	0.029373495	0.039386931
DW with SH						
Space Heating	0	0	0	0	0	0
Water Heating	0	0	0	0	0	0
Cooking	0.155748288	0.195752106	0.262225714	0.35161685	0.471480876	0.632208897
Air Conditioning	0.006592466	0.008285735	0.01109941	0.01488313	0.019956698	0.026759944
Appliances	0.039954338	0.050216576	0.067269149	0.090200789	0.120949684	0.162181481
Electricity - Lighting	0.029109589	0.036586363	0.04901038	0.065717718	0.088120484	0.118160793
Fossil Fuels - Lighting	0.00456621	0.005739037	0.007687903	0.010308662	0.013822821	0.018535026
Total Useful						
Space Heating	0	0	0	0	0	0
Water Heating	0	0	0	0	0	0
Cooking	1.038321918	1.305014042	1.748171425	2.344112333	3.143205839	4.214725979
Air Conditioning	0.236957763	0.297820167	0.398954103	0.534955108	0.717318021	0.961852023

Appliances	0.215753425	0.271169513	0.363253405	0.487084261	0.653128295	0.875779995
Electricity - Lighting	0.12956621	0.162845184	0.21814424	0.292508273	0.392222548	0.525931373
Fossil Fuels - Lighting	0.027968037	0.035151604	0.047088404	0.063140552	0.084664779	0.113527036
Total (Urban)	**1.648567352**	**2.072000509**	**2.775611577**	**3.721800527**	**4.990539482**	**6.691816406**

Source: Author’s construct (2024