UNIVERSITY OF CAPE COAST

MODELLING THE ECONOMIC IMPACTS OF ENERGY TRANSITION RAPIDITY ON THE ELECTRICITY SECTOR IN GHANA

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2024

UNIVERSITY OF CAPE COAST

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BY

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Thesis submitted to the Department of Economic Studies of the School of Economics, College of Humanities and Legal Studies, University of Cape Coast in partial fulfilment of the requirements for the award of Doctor of Philosophy degree in Economics

APRIL 2024

DECLARATION

Candidate's Declaration

I hereby declare that this thesis is the result of my own original research and that no part of it has been presented for another degree in this university or elsewhere.

Candidate's Signature ………………………….……. Date…….……………..

Candidate's Name: Richard Kwabena Nkrumah

Supervisors' Declaration

We hereby declare that the preparation and presentation of the thesis were supervised in accordance with the guidelines on supervision of thesis laid down by the University of Cape Coast

Principal Supervisor's Signature …………………........ Date………………...

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Supervisor's Name: Prof. Isaac Bentum-Ennin

ABSTRACT

The ongoing energy transition demands significant increase in the shares of low carbon energy technologies in the supply mix. The intention is to ultimately phaseout fossil-fuel technologies to keep global temperatures well below 2^{o}C relative to pre-industrial levels. Despite opening clear possibilities to solve global climate challenges, energy transition is significantly front-loaded with plausible economic and social costs. The existing spectrum of literature on the transition in developing electricity markets is yet non-exhaustive, especially for Ghana in the sense of accounting for the economy-wide implication across all sectors of a national economy arising from carbon abatement policies. This study employs forward-looking approaches in computable general equilibrium (CGE) and microsimulation modelling to compute the economic costs associated with accelerated deployment of three transition policies in the electricity sector. The simulated policies include carbon taxes, carbon capping, and renewable energy feed-in-tariffs (REFITs). The simulated polices achieve decent growth in renewable electricity supply but with increasing adverse impacts on growth and welfare rapid penetration rates. Relatively, carbon tax has less adverse impact on welfare than carbon capping through revenue re-distribution. REFITs also make available revenue from ratepayers to fund renewable electricity production albeit accompanied by higher consumer welfare losses as REFITs increase. Finally, a tractable pathway is proposed with minimal impact of each policy option towards decarbonising the electricity sector in Ghana by 2030.

KEY WORDS

Carbon tax

Decarbonation

Computable general equilibrium (CGE)

Electricity

Energy transition

Renewable energy feed-in-tariff (REFIT)

Consumer welfare

ACKNOWLEDGEMENTS

I would like to express my profound gratitude to my supervisors, Professor Emeritus Omowumi Iledare, the former GNPC Chair of Petroleum Commerce at the Institute for Oil and Gas Studies, and Dr Isaac Bentum-Ennin of the School of Economics, for their professional guidance and goodwill towards the successful completion of this work. I am particularly grateful to Professor Emeritus Omowumi Iledare for his unwavering support and encouragement he offered me when the tides were too strong. I am grateful.

I am also thankful to Ghana National Petroleum Corporation (GNPC) for the grant award I received to successful complete this research. Also, colleagues at the Institute for Oil Gas Studies and the School of Economics, my family for their unflinching support throughout this journey, especially my wife, Elizabeth Nsenkyire, and my mother, Abena Nkumaa – affectionately called Obofo.

DEDICATION

To my wife and my mum

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LIST OF ACRONYMS

AEG	Accelerated Economic Growth
AIDS	Almost Ideal Demand Systems
BAU	Business as Usual
CGE	Computable General Equilibrium
GAMS	General Algebraic Modelling System
GH-NDC	Ghana's Nationally Determined Contributions
GLSS	Ghana Living Standard Survey
GSS	Ghana Statistical Service
GWh	Gigawatts hour
KLEMS	Capital, Labour, Energy, Material and Services input
KWh	Kilowatts hour
MtCO2	Metric tons of Carbon dioxide emissions
MW	Megawatts
MWh	Megawatts hour
NDCs	Nationally Determined Contributions
REFITs	Renewable Energy Feed-in-Tariffs
SAM	Social Accounting Matrix
SUBSIM	Subsidy Simulation

CHAPTER ONE

INTRODUCTION

The electricity sector is taunted as a key contributor to the global carbon mitigation efforts towards achieving climate change goals enshrined in the Paris Agreement. The benefits of an energy transition in the electricity sector is projected to be far-reaching, averting global catastrophe manifesting through extreme weather conditions, including flooding in several parts of the world, and widespread food shortages, especially in developing countries (Arora et al., 2018). Despite the opportunities presented by the transition, inherent costs associated with transition pathways in developing economies affect the rapidity of transition.

Background to the Study

Historically, electric power generation has largely been dependent on fossil fuels like coal, oil and natural gas. While oil accounts for a small share of electricity production, coal and gas, especially in developed countries that generate the bulk of global electricity output (Cozzi et al., 2020) . Statistics from *Our World in Data* in 2022, sourced from the IEA in Cozzi et al., (2020), indicates that around 64 percent of global electricity was produced from fossil fuels put together, and a third from coal plants. As a result, as in, the electricity sector together with heating the sector, accounts for nearly half of the changes in anthropogenic emissions, around 7 billion tons of carbon dioxide equivalent (CO2eq) added to the global stock of emissions, over the recent three decades.

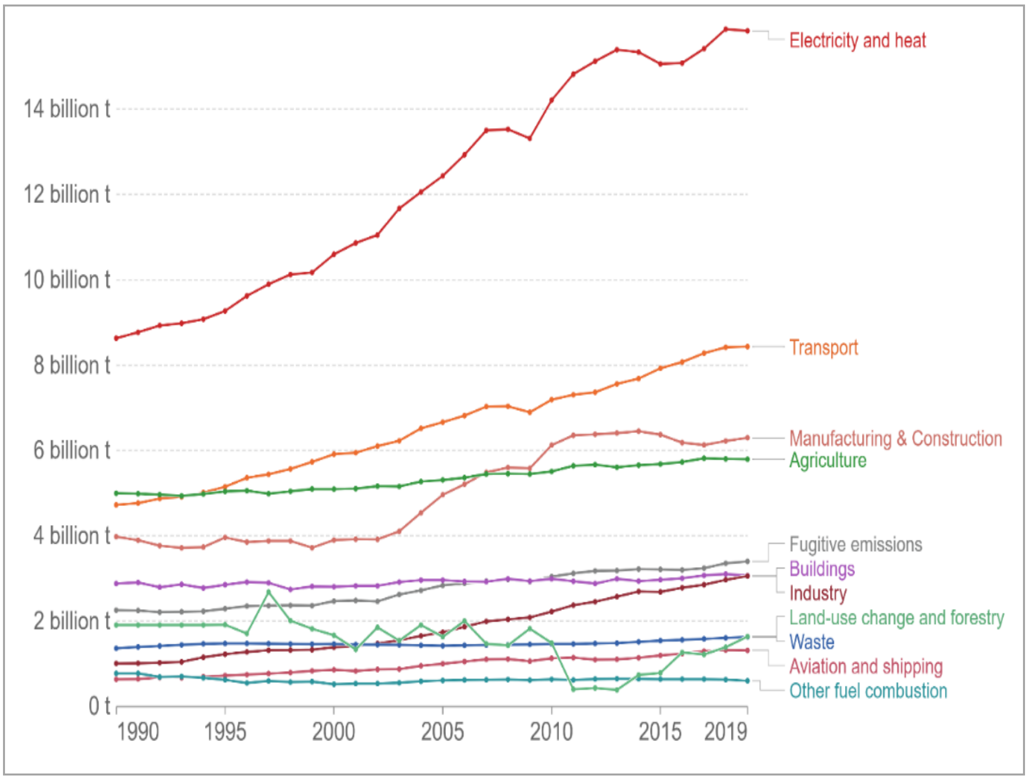

Figure 1: Global Greenhouse Gas Emissions by Sector
Source: Cozzi et al., (2020)

Several climate carbon pricing instruments including carbon taxes, emissions capping and trading systems (ETS), carbon credit mechanisms, and most recently the cross-border adjustments mechanisms (CBAM) adopted by European countries (Bierbrauer et al., 2021; Lim et al., 2021), are part of global efforts to curtail carbon emissions, especially from high polluting industrial processes. Theoretically, carbon mitigation measures impose a price penalty on pollution to penalize unsustainable production and consumption behaviours through price adjustments (Gerbeti, 2021; Grubb & Neuhoff, 2006). On the other hand, as noted by Cherrington et al (2013), feed-in tariffs and auction mechanisms incentivize production and consumption of cleaner energy. Nevertheless, conditions for effective and equitable income redistribution may not exist in developing countries unlike in the developed world.

In developing countries, the electricity sector, albeit underdeveloped, is yet responsible for providing power to support lives and livelihoods, and a spine to the much-needed industrialization in these countries. The sector in developing countries, remains, therefore, a significant player in the global transition. Although cumulative count of carbon emissions by developing countries, apart from the BRICS countries (i.e., Brazil, Russia, India, China and South Africa), constitute a very tiny fraction of global carbon emissions (see, Khan et al., 2014), rising electricity demand to meet the needs of the fast-growing population and rapid industrialisation is causing incremental patterns in GHG (Shahsavari & Akbari, 2018). This rather requires necessary emissions-reduction evolution in the electricity value-chain. The evolution requires increasing significant shares of low-carbon electricity technologies in the supply mix and ultimately phaseout fossil-fuel technologies to augment the global emissions mitigation struggle to keeping global temperatures well below 2^oC.

Thus, under the Paris Agreement, African countries have joined the rest of the world to pledge commitment towards renewable energy expansion in their Nationally Determined Contributions (NDCs) (Ackah & Graham, 2021). These commitments constitute a total of 97,000 MW of installed capacity, equal to 190 per cent of the installed renewable energy capacity in 2019 (The International Renewable Energy Agency, 2020). Around half of these commitments are unconditional – that is, they do not depend on external support. However, in 2019, only 20 per cent of the total installed electricity generation capacity in Africa was based on renewable sources (IRENA, 2022). It is in this vein that Africa’s agenda 2063 also emphasizes proper development of all African energy resources to promote access to modern, efficient, reliable, cost-effective, renewable energy to all (DeGhetto et al., 2016). This is to be achieved while participating in global efforts for climate change mitigation that support and broaden the policy space for sustainable development on the continent.

By extension, Ghana's decarbonization journey in the electricity sector requires deliberate efforts at ramping up production to meet growing demand from households, industry and commercial firms, and keeping low profile on carbon emissions by 2030. Ghana's case is particularly interesting (see **Figure *2***).

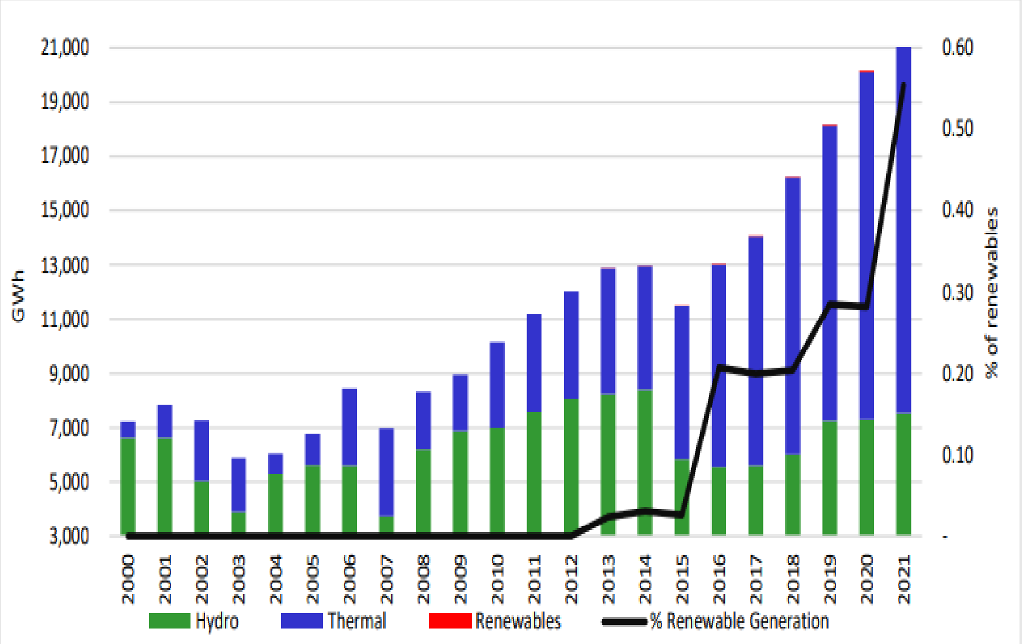

Figure 2: An Account of Electricity Generation in Ghana
Source: Ghana Energy Commission (2022)

Electricity production was largely green from its 1020MW hydroelectricity dam at Akosombo, commissioned in 1965 which remained the country's main source of electricity until the turn of the millennium. Installed generation capacity more than tripled between 2000 and 2021, from approximately 7,000GWh to 21000GWh, and the difference supplied by thermal sources.

By the end of 2021, total grid electricity generation in 2021 was 5,481MW of which 1,584MW (around 29 %) was from hydropower and 3,753MW (around 69 %) was from thermal sources, and the remainder from other renewable sources (Ghana Energy Commission, 2022). The implication of this is fast-rising carbon-dioxide emissions in Ghana's energy sector (**Figure 3**), especially from 2010 when thermal generation almost quadrupled (Ghana Energy Commission, 2022).

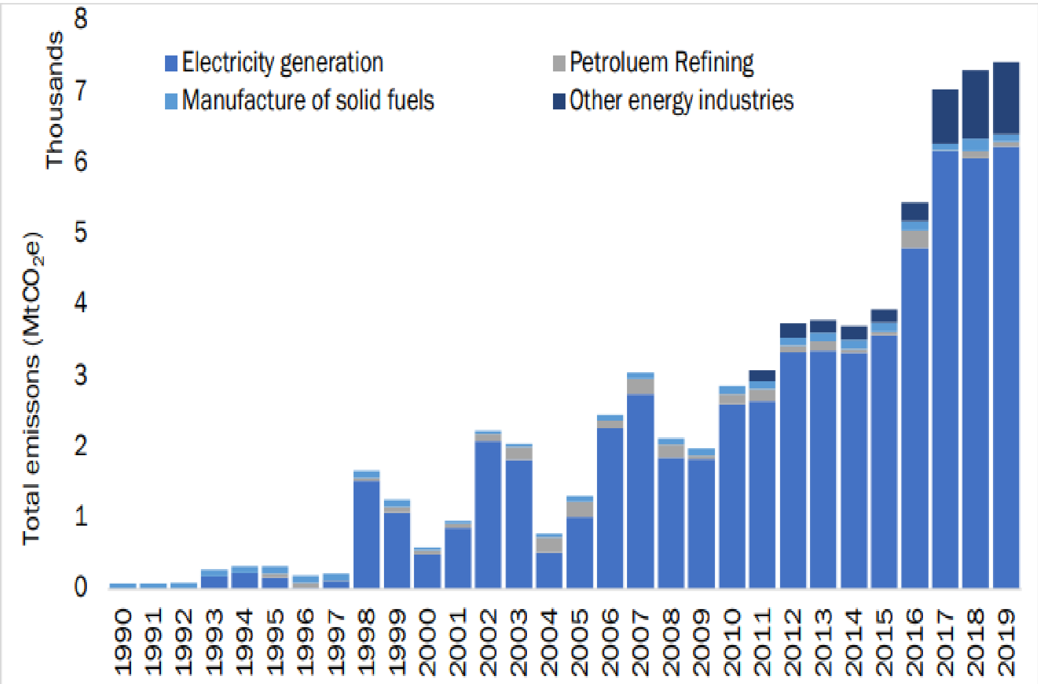

Figure 3: An Account of GHG Emissions in Ghana
Source: Ghana Environmental Protection Agency (2022)

In **Figure** 3: An Account of **GHG Emissions in Ghana**

, the overall GHG emissions in the energy sector in 2019 amounted to 27.30 MtCO2e in 2019, making up 45.7 percent of the national totals, including LULUCF, and 61 percent when the LULUCF emissions are excluded. GHG emissions in the electricity sector dwarfs the emissions from the other energy industries. The observed increases were mainly driven by the rising consumption of natural gas and heavy fuels in thermal electricity generation for the national grid (EPA, 2022).

In the foregoing GHG statistics, the government of Ghana, in consonance with the Paris Agreement, has committed to implementing 47 adaptation and mitigation programmes of action in its nationally determined contributions (GH-NDCs) aimed at reducing GHG emissions, create over one million jobs, avoid 2,900 deaths due to improved air quality by 2030 (MESTI, 2021). Included in the GH-NDCs are two main goals relating to the energy transition: scaling up renewable energy penetration by 10% by 2030; and scaling up 120 million standard cubic feet (MSCF) natural gas replacements of light crude oil for electricity generation in thermal plants. By these twin goals, the country expects to conditionally reduce its greenhouse gas (GHG) emissions by at least 45% by 2030 (MESTI, 2021).

Ghana's NDC has further been expanded into a so-called National Energy Transition Framework, 2022-2070, launched at the Conference of parties (COP) 27 in Egypt, 2022 (see, (Ministry of Energy, 2022)). This framework broadens the scope of programmes and actions in the energy sector to achieving just transition, particularly in the electricity sub-sector. The duration of programmes under this framework extends beyond 2030 to 2070. Under this framework, the government hopes to achieve energy transition at a pace that is just and equitable. Hence, the extension of her commitment to net zero to 2070.

According to Ghana's energy transition framework published the Ministry of Energy (2022), Ghana will seek to 'sustainably' exploit her existing natural resources in commercial quantities, between now and 2070. These resources include natural gas, and new mineral discoveries like lithium and graphite which are essential for battery technologies in electric vehicles (Ministry of Energy, 2022). Furthermore, Ghana seeks to diversify its energy mix to include 21GW of renewable energy, including upscale in nuclear power by 2050, which provides the opportunity to commercialize the renewable energy carbon credit and provide affordable electricity at a generation cost below 4.5cents/kwh (Ministry of Energy, 2022).

However, the current awakening towards net-zero transition on the continent has come at a time where developing countries are devastated by the COVID-19 pandemic. Specifically, the IEA estimates that, at least, 660 million more people, according are estimated to be added to the existing number to approximate about one-fourth of the world's population to live without electricity by 2030, most of them in Sub-Saharan Africa (IEA, 2022). Further exacerbated by the geopolitical war in Europe, the global power systems have been thrown into turmoil where some developed countries, for example Germany, are ramping up abandoned fossil-based plants amid fuel supply shortages and price hikes under harsh weather conditions (Quitzow et al., 2021).

In like manner, developing countries have had to virtually halt national electrification efforts towards the unserved population due to fuel insecurity and price hikes. For instance, Ghana's net-zero transitions by 2070 is estimated to require financing to the tune of US$562 billion, an average of around US$11.5billion per annum; committing around 18 percent of her 2022 GDP annually (Ministry of Energy, 2022). Ghana would have to transition anyway, but what strategic options can Ghana afford in her net-zero ambitions by 2030?

Statement of Problem

The significant gap in decarbonation aspirations and reality in many developing nations is a testament of a low-level alignment of immediate-to-long-term transition costs to politico-economic needs and financial capacity. Ghana, for example, sought to increase penetration of its non-hydro renewable generation capacity from about a percent to 10 percent by 2020 (Ghana Energy Commission, 2019; Ministry of Power, 2015). This was missed, and the target year has since been extended to 2030 (Ghana Energy Commission, 2019; Ministry of Energy, 2022). Yet, as of 2023, renewable energy penetration still hovers around 2 percent (Ghana Energy Commission, 2023).

In economics, significant policy measures aimed at inducing changes in legacy energy mix certainly trigger changes in domestic prices across the whole economy with repercussions for sector growth and real incomes of significant socioeconomic groups. Understanding these economy-wide repercussions is crucial for a study concerned with the obstacles to – and political feasibility of – adopting a low-carbon growth strategy (Willenbockel et al., 2017). Such analysis requires the adoption of a multisectoral general equilibrium approach that allow s the capture of the input–output linkages between the electricity sector and the rest of the economy, as well as the linkages between production activity, household income and expenditure, and government policy (Willenbockel et al., 2017).

It is contended strongly in this study that, framing the task of decarbonisation and carbon abatement in the energy systems as a partial equilibrium phenomenon fails to account for the total ripple effects of policy actions arising from linkages within and outside the energy sector. The failure to account for such total macroeconomic effects of emissions reduction policies also misses an all-important impact of the overall cost to the economy due to emissions-control actions by the government and/or regulatory authorities. Unfortunately, most studies and policy planning toolkits used by countries like Ghana often resort to bottom-up analytical models that provide greater detail of the electricity ecosystem. Prominent among such tools are Long-range Energy Alternatives Planning (LEAP), Integrated Resource Planning (IRP), TIMES/MARKAL, MESSAGE, OSeMOSYS, etc. However, these bottom-up models pay little to no tribute to optimal choices of agents in the macroeconomy.

In this sense, CGE models have been widely used in energy and climate mitigation policy analysis (Arndt et al., 2002; Calderón et al., 2016; Willenbockel et al., 2017). The prime appeal of adopting a general equilibrium approach to energy policy and energy-related environmental policy analysis arises from the fact that energy is an input to virtually every economic activity. Hence, changes in the energy sector 'will ripple through multiple markets, with far larger consequences than energy's small share of national income might suggest' (Sue Wing 2009: 2).

Despite the wide application of the CGE framework in energy-economy modelling, only a handful of literature on Ghana's energy transition in the energy sector adopted the framework to generate useful insights for

Ghana's transition pathways. Most notable among them are Wesseh Jr et al (2016), Wesseh Jr and Lin (2016; 2017), and Willenbockel et al (2017). Works by Wesseh and the team in 2016 and 2017 explored the environmental and welfare impacts of refined oil subsidies removal among oil consumers in Ghana. The study by Willenbockel et al (2017), on the other hand, primarily focused on the electricity sector, exploring the macroeconomic impacts of low-carbon energy transitions for Ghana and Kenya using the CGE framework. The study specifically simulated the prospective medium-run growth and distributional implications associated with a shift towards a higher share of renewables in the power mix, up to 2025. Nonetheless, Willenbockel et al (2017) also investigated in the implications of fuel price shocks at a stated share in renewable electricity penetration.

CGE models may suffer from high aggregation and lack of explicit technology detail about the characterisation of the model's ecosystem. The resultant danger is that simulation results may have biases in the estimated impact if the fundamental principle of homogeneity of technology over whom aggregations are made are quite heterogenous (Böhringer & Rutherford 2008) or violates technical feasibility limits (McFarland, Reilly and Herzog 2004; Hourcade et al. 2006). Moreover, the lack of technological explicitness impedes the ability of top-down models to adequately measure policy effectiveness between alternative energy technologies (Hourcade et al. 2006).

In this regard, this study, like Willenbockel et al (2017) builds a more detailed 'bottom-up' information on energy technology options into the CGE modelling, overcoming the limitations of conventional top-down CGE models. The present study decomposes electricity activity by sources based on the relative share of gross output, and cost. The prime distinguishing feature of this study from the existing literature, especially Willenbockel et al (2017), is the source of shock to the economy. While earlier studies have principally focused on external shocks emanating from the world prices of fuel, this present study models economic shocks from internal, domestic fiscal policies like tax, emissions capping and tariffs.

This is because, the expansion of carbon mitigation initiatives is largely being pursued through deployment of domestic market tools geared towards scaling up decarbonisation in the electricity market. These tools have often included tax-benefit options that seek to discourage the use of fossil-based technologies, on one hand, and incentivising clean and renewable energy technologies, on the other. The most common of these tax schemes have included carbon taxes, cap and trade, while popular incentive schemes include carbon credits mechanisms and renewable energy feed-in tariffs. Inter alia, these domestic policies have reinforced the persistent decline in the unit costs of renewable technologies and increasing availability of financing mechanisms. However, the amplitude of potential impacts of each market tool presents a new challenge of understanding the political feasibility of each transition pathway.

Aim of the Study

The aim of this study is to assess the impact of energy transition rapidity and strategic options for the electricity sector of Ghana. The strategic options evaluated in the analysis include three common pathways in the transition policy space: carbon taxation, carbon capping, and renewable energy feed-in-tariffs (REFITs). The study achieves this using computable general equilibrium (CGE) modelling and microsimulation approaches. By unravelling the impacts of transition pace in the electricity sector, the results obtained become a useful guide for policymakers in underdeveloped electricity markets like Ghana that seek to ramped up efforts towards energy transition.

Objectives of the Study

The aim of this research is pursued through the inter-link for three most common transition pathways for developing energy markets, that is, carbon taxes, carbon capping and renewable energy feed-in-tariffs (REFITs). Each of the specific objectives, therefore, estimates the impacts of a specific transition pathway on the national economy, the energy sector and consumer welfare. They are as follows.

i. To compute the level of impact of carbon-tax options on economic growth and welfare. Under this objective, the study analyses three incremental but hypothetical scenarios of tax rates relative to the conditional and unconditional carbon-abatement commitments contained in Ghana's updated NDCs for 2020-2030.

ii. To determine the impacts of a carbon capping policy on growth and consumer welfare. This objective also follows the scenario paths of carbon tax in (i), except that carbon capping is a restriction on the quantity (metric tons) of carbon emissions permissible under emissions caps.

iii. To estimate the effect on growth and consumer welfare from feed-in-tariffs for solar PV penetration. In this objective, growth in electricity demand and consumer welfare are assessed in the light of feed-in tariffs which are computed as a consumption tax on price of electricity.

Research Questions

For the foregoing research gap analysis, aim and objectives for the study lead to the following thesis questions regarding Ghana's quest for energy transition in the electricity sector.

i. How does a carbon-tax policy for the purpose of carbon mitigation in the electricity sector impact on economic growth and consumer welfare?

ii. What level of impact does a carbon-capping as a mitigation policy have on economic growth and consumer welfare?

iii. In what ways does feed-in-tariff impact growth and consumer welfare?

Further, in each of the above research questions the study asks, how does the pace of transition influence the level of impact of the strategic policy option on the national economy and welfare?

Relevance of the Study

This research is timely for developing countries, like Ghana, that have limited access to finance, technology and investment towards energy transition enshrined in the GH-NDCs. By providing ex-ante analysis of potential domestic pathways and pace to energy transition in the electricity sector, this study provides a basis for adequate tax-benefit policy designs for Ghana that are less to non-distortionary with respect to growth and welfare. The study, therefore, is crucial for navigating the underdeveloped electricity markets like Ghana in seeking to engineer domestic tax efforts, for instance, towards the energy transition that will be politically acceptable.

Delimitation of the Study

This study is primarily concerned with Ghana's electricity sector. Like the rest of the continent, the electricity sector in Ghana is faced with several challenges that are also common to the rest in the sub-region. These include insufficient power generation resulting in power shedding as was experienced few years ago but now with oversubscribed capacity which is currently ballooning the public debts. Hence, changing course from legacy power systems to clean sources will require substantial but tacit financing schemes that are without adverse consequences for economic growth and welfare.

Again, the focus of the study is further narrowed on grid electricity only. That is, embedded or off-grid electric power generation is beyond the scope of this study. In that way, gross output and demand are reported values of total electricity supplied and consumed on the national grid, respectively. It is worthy of mention that, this does not, in any significant way, bias the result given the national electricity access rate of 82%, making grid electricity most of the total electricity generated and consumed in any given year.

Organisation of the Study

This thesis is organised in five chapters. The first chapter, including this section, provides an overview to the study and discusses the thesis background and research problem; research questions, aim, objectives of the study; overview of research methods and delimitations; and a highlight on the study's contribution to knowledge. The second chapter synthesizes theoretical and empirical literature on production and producer behaviour linked with the green revolution (referred to in other studies as energy transition, green growth, green industrial revolution, among others) in developed and developing countries in general and specifically on the impacts of the transition on developing countries.

Moving on, Chapter Three discusses the research methods, including the design, analytical and conceptual frameworks, theoretical and empirical models, data type and sources, and the estimation technique. The next chapter, Chapter Four, discusses, inter alia, the brief and specific research methodology and empirical results for each specific policy options: (i) carbon taxation, (ii) carbon capping, and (iii) renewable energy feed-in-tariff for solar electricity, respectively. Put in three sections in Chapter Four, the empirical results are discussed on the simulated impacts on economic growth and welfare losses inherent in each policy pathway. The last chapter, Chapter Five, summarizes the entire thesis into a long abstract and presents the conclusions and policy implications based on the empirical results in the preceding chapter. Finally, the fifth chapter ends by acknowledging the limitations of the study and advances proposals for further research.

Chapter Summary

Up to this point, this first chapter has laid out the all-important background, research problem, aim and the specific objectives for understanding the impact of transition rapidity and strategic options on Ghana's electricity sector. It is argued in here that carbon abatement strategies in the energy systems have to account for the total ripple effects of policy actions arising from linkages within and outside the energy sector. The failure to account for such total macroeconomic effects of emissions reduction policies also misses an all-important impact of the overall cost to the economy due to emissions-control actions by the government and/or regulatory authorities. Unfortunately, most studies and toolkits used by countries like Ghana for energy policy planning do not provide the wider detail of the energy-economy ecosystem.

This current study, therefore, seeks to set out an economy-wide model in a CGE framework to unravel the impacts of energy transition rapidity and strategic options Ghana's electricity sector. Specifically, the study will seek to compute ex-ante impacts of carbon-tax and capping options, as well as feed-in tariffs on economic growth and welfare. By so doing, it provides a basis for adequate tax-benefit policy designs for energy transition in Ghana that are less to non-distortionary with respect to growth and welfare. In the next chapter, relevant scholarly literature on energy transition in the electricity sector, the CGE methodology and renewable energy financing schemes are reviewed.

CHAPTER TWO

LITERATURE REVIEW

In the ongoing global energy transition, the electricity sector is an important player in meeting the global targets of carbon mitigations. A greater share of the mitigation changes along electricity value change must occur at the supply side. To understand these changes, this study provides a critique of the theoretical basis for what needs to happen in the decarbonization of the energy sector, which is accompanied by multiple rebound effects from interlinked markets occurring in a neoclassical general equilibrium framework. Before critiquing this theoretical framework, a spotlight is first thrown on the neoclassical formalisations on producer behaviour and how markets interact iteratively to achieve a general equilibrium in prices and consumption bundles. Lastly, empirical studies of the effects of carbon mitigation in the electricity sector usings methods like general equilibrium modelling, inter alia are synthesised.

Theoretical Review

This section synthesizes theories of relevance to the study. The section proceeds with discussions on the theory of production and connects to the Pigouvian pollution tax and adjustment costs in the circular economy and a general equilibrium framework. A critique of the general equilibrium theory is presented in the end.

Theory of production and inputs substitution

Broadly, production consists of the transformation of factors of production into goods and services. Economists postulate that the production process is owned by a producer (individual or firm), whose motive is to maximize profits, takes decisions regarding the employment of inputs, in a two-input case: labour (L) and capital (K), at a given level technology (Banerjee & Duflo, 2005; O'Mahony & Timmer, 2009). Recent extensions in the production specifications include energy (E), material (M) and services inputs (S) in a so-called KLEMS technology (Balk, 2021; Lagomarsino, 2020). The production function is of the form $Y = f(K, L, E, M, S; A)$. Thus, the producer chooses inputs and decides what to produce, how much to produce and how to produce.

These choices, albeit rest with the producer, several systematic and idiosyncratic factors can affect the optimality of the individual choices. Further, by aggregating the resultant outputs across individual producers results in summed value of output often referred to as the gross domestic products (GDP). This is only possible by the neoclassicals' assumption that there exists an aggregate production function that describes the technology of an entire economy. By this assumption, output choices of individual production units at the micro economy level can be consistently aggregated into a macro-output (GDP). Hence, gross output can be accounted for by the changes in the aggregate production accounted for by factor inputs and some simple measure of the level of technology in the economy as a whole (Nelson & Winter, 1974). Although studies like Felipe and Fisher (2006) question the empirical legitimacy of this assumption, several other studies have endorsed its applicability using real data.

A key assumption underpinning the aggregate production function is that all factor markets are perfect and, thus, each market allocates the available supply of inputs to maximize total output (Dillon & Barrett, 2017; Hunt, 2007). Under the assumption of perfect markets, decisions of individual producers become insignificant amongst the multitudes of market agents. Alternatively, an aggregation of outputs over all producers is not affected by the characteristics of the production function of a single producer.

So, according to Banerjee and Duflo (2005) the concavity of the aggregate production function is preserved even if individual production functions are not. These two properties: irrelevance of decisions of the individual producer and concavity of aggregate output, founded on the assumption of perfect competition, permit the aggregation of micro production. In that way, the neoclassical theory is able to reasonably explain the broad patterns of economic change across countries, by simply observing the aggregate production function (Banerjee & Duflo, 2005). This gives an impetus to addressing global concerns like climate change, output and input supply, and technical advancements by affecting the production functions of individual producers at the microeconomy level.

The production cost function which indicates the total cost C of producing a given level of output, given prices of the inputs and the state of technology, A. The cost function can be written as $C = g(K, L, E, M, S; A)$. A number of econometric studies have shown factor substitution between energy and labour in nested function of inputs (Costantini et al., 2019; Henningsen et al., 2019; Keen et al., 2019). Therefore, in a situation of a price increment in one input, all other things remaining the same, it will induce substitution away from the input in question to the another. So, using labour and energy input substitution, for example, as the price of labour increases, ceteris paribus, firms substitute away from labour and towards energy, and vice versa.

On the other hand, capital and energy are deem complementary. In that case, an increase in price of energy will decrease firms' demand for both energy and capital inputs. The elasticity of substitution which is a unitless measure of how various inputs substitute for each other attempts to measure the curvature of the lower boundary of the input requirement set (Stern, 2011). But the sum of output elasticities for each input is the elasticity of scale. If it is less than one, then the technology is said to exhibit decreasing returns to scale and isoquants spread out as output rises; if it is equal to one, then the technology exhibits constant returns to scale and isoquants are evenly spaced; and if is greater than one, the technology exhibits increasing returns to scale and the isoquants bunch as output expands. The returns to scale from increasing all of the inputs is thus the average marginal increase in output from all inputs, where each input is weighted by the relative size of that input compared to output.

The Pigouvian pollution tax and adjustment cost

The energy transition entails a paradigm shift from fossil fuels that pollute the environment to cleaner sources of energy to safeguard the global climate. It is therefore required of firms to accelerate the consumption of cleaner energy, reduce fossil fuels in energy production and use. Thus, firms in the energy markets are persuaded to shift from away from fossil-fuel-based technologies. Hence, Pareto optimal allocations require governments to impose a Pigouvian tax on either amount of pollution in production or gross output (Baumol, 1972). It is fair to assume that some resources would be allocated to antipollution activities. As it is true for the other type of preventive measures, society should forgo some resources for the collection and imposition of taxes. These foregone resources can be interpreted as the cost of taxation. As firms are required to invest in pollution reduction, they face adjustment costs. Scholars like Beavis (1979) argued that taxation when used as a preventive measure against pollution is also subject to adjustment costs. The adjustment cost manifests as a loss in output arising from the difficulty of undertaking new investment to absorb pollution tax in a certain time interval (Bertola, 1988; Bertola & Caballero, 1994).

Thus, assuming irreversibility or partial reversibility of investments implies costs to the firm when it wants to undertake new investments. Therefore, individual firms critically appraise any additional investment when there is a positive shock to the demand of its inputs or outputs and, hence become sticky in response to the shock (Bertola & Caballero, 1994). According to Dixit (1989), a firm still chooses to invest if the net present value (NPV) of a cumulative shock exceeds the opportunity cost of not investing. Thus, adjustment costs associated with disinvestments including severance payments to laid-off workers, sunk costs and waste charges on abandoned capital goods may force firms to continue to operate, though sub-optimally. The net effect of an adjustment cost to the upside and downside of the shock may result in episodes of no activity for the firm (Dixit, 1989).

That is, the presence of market rigidities protracts a firm's decision to add to existing stock of capital or to disinvest. As a results, uncertainties in the energy market will stay the hands of firms to choose a course of action in favour or against the pollution, thereby creating sub-optimal choices in new investment or prolonging the status quo. In their book, Dixit and Pindyck (1994), demonstrates that a firm's sunk costs cause hysteresis in investment defined as a failure of an effect to reverse itself after its underlying cause is reversed.

The market price P evolves exogenously, stochastically and dynamically over time: $dP/P = \mu dt + \sigma dz$. Dixit showed that for a firm that invests an amount, k, to be active in the market and a lump-sum cost, l, to exit the market. If a firm exits and later decides to reenter also invests k amount. . Dixit (1989), therefore, showed that there exists a price that triggers a firm's entry, $P_H > w + \rho k$, greater than the usual full cost (w = variable cost; ρk = interest cost of capital) and price that triggers exit, $P_L > w - \rho l$. At a price between these limits, an idle firm does not invest, and an active firm does not exit.

Therefore, in all cases, a firm's optimal decision rule consists of two triggers, P_H and P_L, with P_H > P_L, such that the investment should be made if P rises above P_H, and should be abandoned if P falls below P_L as shown in **Figure 4**. Dixit and Pindyck (1994) showed that, hysteresis remains significant for any small uncertainty. That is, even a little uncertainty matters a lot. Dixit (1989), however, stated without proof that for an increase in interest rates, investment is reluctantly made and more easily abandoned.

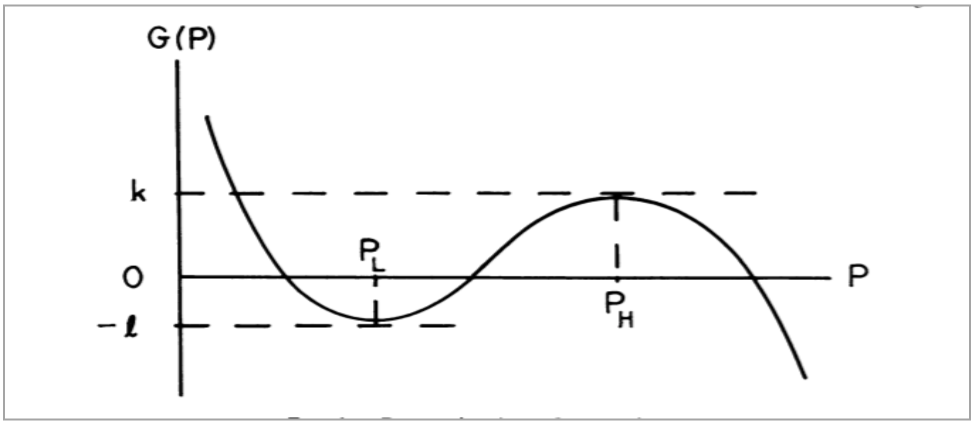

Figure 4: Trigger for Firm Entry and Exist
Source: Dixit (1989)

By this, Dixit (1989) argued that even if there is no exit cost as such (I = 0), the exit trigger remains P_L below w. The firm knows that by remaining active it can avoid incurring k for re-entry should future developments turn favourable; therefore, it is willing to incur some current loss to preserve this option. Basing on earlier works on the optimal investment behaviour under uncertainty (Abel et al., 1996; Abel & Eberly, 1994, 1996, 1999). Now, consider for a moment, that pollution tax is levied on the polluting firm in the electricity sector. This shifts the cost curve upwards, all other things remaining the same. It is expected of the firm to reduce substantial investments in the polluting technology to neutralise the rise in costs.

However, according to (Pindyck, 1982), a risk-averse firm would choose suboptimal levels of disinvestment due to adjustment costs partly due to market rigidities and uncertainties. Hence, a firm that produces electricity (Q) using capital (K), labour (L) and 'dirty' energy resource (F) as inputs, at a given technology (A), in a nested CES function will not exit so far as the cost of exiting exceeds the future value of its average variable cost $l > w/\rho$ (Dixit & Pindyck, 1994). This is important for the analysis of firm behaviour under the energy transition whereby firms with high carbon footprints face imminent market exit.

General equilibrium theory

Now, attention is focused on discussing the general equilibrium theory that connects the product market, and the producer choices therein as identified above with the inputs, intermediate goods, and final goods and services market. The general equilibrium (GE) theory by Leon Walras (1834-1910) is a fundamental paradigm used by economists to explain how resources are efficiently allocated in decentralised markets. Hitherto, partial equilibrium analysis provided limited insights into the role of price in equilibrating demand and supply in a single market at a time. However, real-world situations necessitated an extension from this partial equilibrium in a single market to general equilibrium that reflects the idea that supply and demand in a single market depend on the prices of other goods in several other markets. Hence, it may not be legitimate to speak of equilibrium with respect to a single commodity without the simultaneous influences from connected markets in an economy. Hence, Walras' formulation in 1874 of a multi-market framework came to be known as general equilibrium, or Walrasian equilibrium.

Alternatively, general equilibrium framework explains how supply and demand in an economy with many markets interact to culminate in an equilibrium of prices. The general equilibrium framework of Kenneth Arrow and Gerard Debreu, as well as Lionel McKenzie where all economic agents optimize their objective functions and are in equilibrium (Düppe & Weintraub, 2014). proved the existence of a general equilibrium under Pareto efficient outcomes and price competitive by applying the fixed-point theorems of Brouwer and Kakutani (Arrow, 1974). This excellence of scholarship became pivotal for modern application of the theory to understand how interlinked markets achieve equilibrium under perfect competition assumptions. Since then, GE models have been applied to study the economy-wide and, in some cases, regional impacts of changes in economic decisions and exogeneous shocks (Geanakoplos, 1989).

Formally, according to seminal works of Arrow and Debreu, GE becomes a vector of prices that maximize every agent's consumption utility, and clears the market after each agent's total demand for each commodity just equals the aggregate endowment (Arrow, 1974). As a result, as Tesfatsion (2006) argues that, GE in modern-day form is a set of conditions under which feasible allocations of goods and services can be price-supported in an economic system. The economic system must be organized based on decentralized markets with private ownership of productive resources. These conditions postulate the existence of a finite number of price-taking profit-maximizing firms, a finite number of consumers with exogenously determined preferences and a Walrasian Auctioneer that determines prices to ensure each market clears (McAfee & McMillan, 1987). The concept of general equilibrium thus gave birth to what is well known as the circular economy.

The circular economy and general market equilibrium

The circular economy describes the exchanges between economic agents. Key assumptions include, a fixed finite number of consumers whose preferences over different bundles of consumption goods and who own nonnegative initial endowments of capital goods and labour The preferences of each consumer are exogenously given and can be represented by a utility function. There is also a fixed finite number of distinct consumption good and capital good types. Each good is private in the sense that it is both excludable and rival, where excludable means that people can be excluded from consuming the good and rival means that one person's consumption of the good reduces the amount available for consumption by others (J. Robinson, 1979).

Additionally, there is a fixed finite number of firms that produce consumption goods for sale to consumers using labour services and capital services purchased from consumers as inputs to production. Consumers are the ultimate owners of capital and labour inputs used by firms in production activities (Cova, 1997). Therefore, they receive dividends in proportion to their ownership shares. Markets for services and consumption goods are complete. This means that, for each valued service and consumption good, there is a market price at which it can be bought or sold (Aspers & Beckert, 2011; Barzel, 1982).

Consumers, taking expected goods prices, wages, rental rates, and dividends as given, choose demands for consumption goods and supplies of capital and labour services to maximize their utility subject to a budget constraint (expenditure less than or equal to expected income) and physical feasibility conditions (nonnegativity and endowment constraints) (Baxter & King, 1993). Firms, taking expected goods prices, wages, and rental rates as given, choose supplies of goods and demands for capital and labour services to maximize expected profits subject to technological feasibility conditions (nonnegativity constraints, and production relations associating inputs with possible outputs) (Treacy & Wiersema, 1993). Above all, all purchase and sale agreements are 'costlessly' arranged and enforced (Armstrong & Hagel, 2009).

Neoclassical economists argue that general equilibrium is possible by the concept of free market in which flexibility in exogenous price, wage and interest rate creates the conditions necessary for equilibrating the markets, at full employment (Dillon & Barrett, 2017; Hunt, 2007). Hence, without government and external interventions, except to enhance the free operation of markets and a balanced budget, flexible prices can clear the market. Therefore, in a context dominated by perfect competition, scholars like Dubey et al., 2005, Hudea, 2015, Novshek and Sonnenschein, 1987 believe that without protectionist restrictions and in the absence of any form of monopole or unfair competition, the economy succeeds in continuously reaching the natural level of GDP, its self-adjusting mechanisms laying the grounds for quick rebalance in case of steady state deviations.

Full employment is deemed to be characteristic to any freely functioning economy (Beveridge, 2014). Even in disequilibrium standings, with some unemployment level, the equilibrium is re-established by lowering the wages, naturally resulting in an increase of the labour demand and, therefore, in the reset of the initial equilibrium (Nelson & Winter, 1974). Equilibrium is also obtained in case of inequalities between the level of savings and investments. As argued by Lange (1945), lowering of the investments weight in total available incomes diminishes the demand for money and leads, indirectly, given the intention to stimulate it, to a decrease of the interest rate, thus becoming attractive for any potential investors who would re-establish the market equilibrium.

Altogether, the extensive experimentation with computable general equilibrium (CGE) models to generate a greater degree of understanding broad policy issues including economy-wide impact assessment of economic, environment and climate policies has been phenomenal. Most of these computational general equilibrium analyses have been implemented using the General Algebraic Modelling System (GAMS) and the General Equilibrium Modelling Package (GEMPACK) software, among others.

Criticisms of the General Equilibrium theory

Notwithstanding, the general equilibrium approach has some limitations in its applicability to general subject areas and economic issues (Shoven & Whalley, 1992). The most prominent drawback, according to Shoven and Whalley, is the complexity of the computational models, including large number of parameter and variables embedded in complex functional relationships that make econometric estimations pretty tedious. As a result, econometric validation of the computational model is usually lacking because model functions are not fitted with historical data. In this regard, a number of econometric tools have been developed that estimate behavioural parameters using empirical data, big data and machine learning approaches (Fagiolo et al., 2019; Kydland & Prescott, 1996; Windrum et al., 2007).

The complexity in model equations also necessitates large data with is often unreliable and uncertain, especially models that rely on external sources for elasticity estimates (House-Peters & Chang, 2011). Data uncertainty of great concern with general equilibrium models, especially because the parameters' value is very important for later determination of results from different simulations (Arndt et al., 2002). Hence, the quality of data selected for econometric models becomes crucial as it directly affects the quality model results.

Whereas in econometric models, stochastic distribution tries to reduce errors in measuring endogenous and exogenous variables, but the model calibration process of computational general equilibrium models is deterministic and stochastic process is non-existent. So, for most externally-sourced elasticity parameters, the applicability particularly becomes challenged as the assumptions governing their estimation differ across jurisdictions. Hillberry and Hummels (2013) argued that this shortcoming is overcome by empirically estimating behavioural parameters or obtaining data on behavioural patterns from the most identical jurisdiction with less variation in agents' behaviour. The latter is to ensure that errors in behavioural estimates become insignificant.

Moreover, the deterministic feature of general equilibrium models is addressed in recent application of general equilibrium models by the attempts to incorporate dynamic policy response to deal with capital mobility, dynamic changes in interest rates, and endogenous and recursive intertemporal capital accumulation (Bovenberg, 1988; Diao & Thurlow, 2012). For instance, models have attempted to include vintage capital with limited or alternative use once an economic policy renders existing capital obsolete (Campbell, 1998; Petri, 2004). These models can build into decision-making process regarding new capital investment the consequence of policy changes in the future that could render a certain type of physical capital economically obsolete.

Lastly, a few researchers believe that general equilibrium modelling has limited applicability to developing economies due to their peculiarities. They contend that the limited use of general equilibrium models for analysis in developing economies is attributable to their formulation, implementation, and description when typically patterned after those models used in developed economies (Bandara, 1991; S. Robinson, 1989). The general equilibrium models applied in developing countries are more often than likely not non-consistent and non-reflective of the dynamics of the developing economy's adjustment processes (Shobande et al., 2020). Fortunately, there are a number of new studies like Rotemberg and Woodford (1993) that have flexibly modelled non-competitive market structure, representing a paradigm shift from the traditional perfect competitive models to analyse many important issues as they pertain in developing countries. Additionally, some other studies have incorporated economies of scale and product differentiation to enhance a better explanation of trade and trade flow (De Santis, 2002; Harris, 1984; Helpman, 1981).

Overall, the general equilibrium model has got several strong advantages that have influenced a plethora of impact studies in policy spaces in economics and environment. It is agreed in the economic literature that general equilibrium provides. Due to its strong foundation on well-established axioms and the microeconomic principles, the general equilibrium model provides conceptual consistency ideal for model analysis. For instance, under Walras law, households are presumed to be on a binding budget and, also, demand and supply are equal for all commodities and production factors.

In addition to its conceptual consistency, the social accounting matrix, which is an important database for general equilibrium models, ensures data consistency. A suggestion that expenditure cannot exceed incomes and consistent factor allocation makes sure market clears. Another benefit of the general equilibrium model is the analysis of multi-sector backward and forward linkages. Hence, they permit analysis of resource allocation and how policy impacts or permeate through the various sectors of the economy. A major strength here is that it allows for welfare analysis, particularly in a gain or loss situation which helps for compensatory and economic reforms

Empirical Review

This section reviews empirical studies related to the study under eight subsections. In the first five subsections, the author reviews literature on carbon taxation; carbon tax and economic growth; carbon tax, energy price and welfare; carbon tax, revenue and cash transfer; and finally, some criticisms of carbon taxation. Also, renewable energy feed-in-tariffs (REFITS), its global distributional impacts, and impacts in Africa are also discussed in the last three subsections.

Empirical Review of Carbon Taxation

Economists believe that the cost of pollution to society are not often reflected in the market price of private goods and services (Nordhaus, 2021; Stern & Stiglitz, 2021). Hence, by imposing a pollution fee equal to the social cost of carbon corrects this market failure and restores the market to an optimal equilibrium. In this regard, carbon tax is justified as a Pigouvian fee that corrects a market failure caused by environmental externality in production and consumption activities (Dasgupta, 2021; Falcone, 2020). As a result, many countries have adopted carbon pricing, including carbon taxes, as vehicles for meeting their emission abatement targets set under the Paris Climate Agreement (Timilsina, 2022). As shown by Best et al (2020), the average annual growth rate of CO2 emissions from fuel combustion has been around 2 percentage points lower in countries that have had a carbon price compared to countries without it.

Also, a review of literature by Köppl and Schratzenstaller (2023) revealed an increasing number of studies that provide evidence to support the effectiveness of carbon taxes to reduce carbon emissions or at least dampen their growth. Policy effectiveness on carbon emissions has been documented in Finland (Steckel & Jakob, 2021), Brazil (Moz-Christofoletti & Pereda, 2021). reducing inequality gaps in access (Jakob et al., 2016). Several other empirical studies corroborate this stance, although a section of literature espouses divergent findings. Prominent controversies in literature, however, have been about the impact on economic growth, energy access, competition and regressivity of the taxes. These are examined in detail in the following paragraphs.

Carbon tax and economic growth

To begin with, Coffman et al., (2023) employed a baseline scenario using the Renewable Portfolio Standard (RPS) of Hawaii as a policy tool towards decarbonization in the power sector by 2045 in addition to four carbon tax policy scenarios. The authors found carbon tax imposition has a negative impact on economic growth – not even the coupled-effect of tax revenue redistribution to households could reverse it. Also, In South Africa, Arndt et al. (2016) experimented three decarbonization scenarios in addition to a baseline scenario for the electricity sector up to 2035 using carbon tax and import regulations as policy tools. The authors, Arndt et al, found that the use of carbon taxes with no import restrictions affected electricity prices and increased the production cost of energy-intensive economic sectors. These were found to further lead to a reduction in employment and GDP.

Another study in Indonesia by Dissanayake et al. (2020) found that carbon tax has negative effects on economic growth. Also, by employing both general and partial equilibrium models, Calderón et al., (2016) analysed three scenarios in addition to a business-as-usual scenario for reducing CO2 emissions by 2050 in Colombia. By employing a CGE model, the Calderón and the team analysed CO2 reduction scenarios with emissions targeting and carbon taxes as policy mechanisms and found decarbonization scenarios associated with carbon tax imposition to have negative impacts on national consumption and GDP. Likewise Xie et al. (2020) also examined and found 10 decarbonization scenarios affected the demand and supply of energy, which in turn affected the demand and supply of labour and consequently lead to economic losses in GDP and household welfare.

Carbon tax, energy price and welfare

Apart from the impact on growth, carbon pricing in the form of carbon tax often results into higher energy prices and widening inequality among consumers. Fremstad and Paul (2019) argued such a tax exacerbates inequality since low-income households spend a greater share of their income on carbon-intensive goods. Steckel and Jakob (2021) used the computable general equilibrium model and identified negative effects of carbon tax on the social welfare of Finns. Moz-Christofoletti and Pereda (2021) found a shortfall in consumer welfare in Brazil. Furthermore, Känzig (2023) explored features of the European carbon market and documented that a tighter carbon pricing regime led to lower emissions and more green innovation but also higher energy prices. The higher prices are borne unequally across society with poorer households becoming more exposed because of their higher energy share and, importantly, also experience a larger fall in income.

Similarly, Ćorović et al (2022) suggested that lowering CO2 emissions while ensuring efficiency and uninterrupted power supply is the biggest challenge for the market Serbian electricity market as, they argued, decarbonizing the market by limiting fossil fuel electricity generating facilities results in reduced supply and higher tariffs. With this perspective, Patt and Lilliestam (2018) viewed carbon taxes as a dangerous political distraction. Like Levi et al (2020) and Malerba et al (2021) also observed, political economy costs of carbon pricing leads to fears of high unemployment, poverty and lack of access to basic services. These challenges in the political economy make the effectiveness of carbon pricing doubtful (Tvinnereim & Mehling, 2018).

Also, by focussing on collaboration between 28 European countries towards decarbonisation, Mier et al (2023) modelled scenarios for the developmental processes of the European electricity market till 2050 using a CGE model. The authors found that decarbonization of the electricity market will lead to higher electricity prices for consumers and higher rent for producers.

Carbon tax, revenue and cash transfer

Some studies on carbon taxes have gone steps further to analyse the effects of revenue recycling through redistribution to households to mitigate the impacts of price hikes due to carbon taxation. These include, among others, Franks et al. (2018), Bergh and Botzen (2020), Fremstad and Paul (2019) who showed that carbon pricing could be a particularly attractive policy option where domestic revenues from carbon pricing could contribute substantially to financing the Sustainable Development Goals.

Franks et al. (2018) particularly emphasised that carbon taxes could be used to foster growth in an equitable way by returning the revenue as household rebates to support poorer sections of the population, investing in low-carbon infrastructure, and fostering technological change. Dorband et al (2019), together with Bergh and Botzen (2020) argued that if carbon pricing could be complemented by appropriate neutral fiscal transfers, it would become fair. Therefore, devoting carbon tax revenue to fund a carbon dividend makes the policy progressive, minimizes redistribution among households of similar means, as also asserted by Fremstad and Paul (2019).

The above position is again corroborated by Tvinnereim and Mehling (2018). They also argued that carbon pricing, including carbon taxes, generate the revenues needed to fund a financial support program, and these support programs account for all, or nearly all, of the observed changes in emissions and technology investment. That is to say, it is the use of revenues from carbon prices, not the carbon prices themselves, which trigger change. In that regard, Moz-Christofoletti and Pereda (2021) recommended that carbon tax designs be complemented with compensation mechanisms especially in the context of a highly complex tax-system to alleviate the negative impacts on welfare. Saelim (2019) found carbon tax could even become progressive in Thailand under revenue-recycling scenarios by expanding social transfer programs. Saelim specifically mentioned that when carbon tax revenues are recycled through pensions for elderly people, carbon tax is able to reduce poverty rates and improve the welfare of households in the lowest quintile.

Criticisms of carbon taxation

Apart from the opposition against carbon prices due to consumer welfare losses, other scholars like Rosenbloom et al. (2020) entirely reject the efficiency rationale for implementing a carbon price. They argue that climate change ought be more appropriately understood as a system problem than a market failure and that effectiveness must be prioritised over efficiency. Jenkins (2014) real-world implementations of carbon pricing policies can thus fall short of the economically optimal outcomes envisioned in theory.

Scholars of this school of thoughts argue that apart from the political tensions arising from higher energy prices that stall progress in CO2 mitigation efforts, the world is likely not to achieve the required targets of carbon abatement with carbon pricing (Finon, 2019). Carbon pricing might not be appropriate as the main element of the carbon policy package in emerging and developing countries (DCs), because the political economy constraints are greater than in developed countries. Finon, instead, suggested non-price instruments and policies such as efficiency standards, market-oriented regulation, subsidies for clean technologies and public programs involving low carbon infrastructure should be preferentially developed to deal with market and regulatory failures, which are more widespread than in developed countries.

Renewable energy feed-in-tariffs (REFITs)

By design, renewable electricity feed-in tariffs (REFITs) are basically financial mechanisms that provide long-term price guarantee for electricity generated using renewable sources (Meyer-Renschhausen, 2013). Thus, REFITs provide financial stability to renewable energy investors through long-term pricing that are usually higher than prevailing market price of electricity. The price incentive built into REFITs is essentially because current market prices of electricity are not cost-efficient enough for renewable sources to compete favourably with legacy fossil-fuel-based technologies.

For the past decades, adoption of REFITs has made significant impacts on renewable energy (RE) supply and innovation at lower costs compared to alternative policy mechanisms. According to IRENA (2022), the recent decade has witnessed significant domination of renewable generation in procured capacity in Africa. This was possible largely due to innovative financing like REFITs. REFITs, in particular, accounted for about 90 percent of all renewable energy capacity additions in Africa between 2015 and 2017 (ibid).

However, REFITs also create economic pressures due to rising electricity prices which can inhibit industry expansion and negatively affect household savings. In most African countries, already, prices of electricity remain high vis-à-vis the national per capita income. This is after the suffering industry sectors have cross-subsidized prices for residential consumers (Coady et al., 2023). Thus, electricity prices have become a thorny political tool in most African countries.

Scholarship has shown the role of REFITs to reducing investment risks into renewable energy technology and drive renewable energy production, especially in industrialised countries (Alizamir et al., 2016; Bersalli et al., 2020; Górnowicz & Castro, 2020; Zhang et al., 2019). The appropriateness of a REFIT design is, however, market-dependent based on prevailing economic environment (Ramli & Twaha, 2015). Hence, REFIT designs in different jurisdictions would differ composition and effectiveness. Therefore, while there are less successes in the Africa (IRENA, 2022) and elsewhere (Böhringer et al., 2014; Lagac & Yap, 2020), other studies have shown its effectiveness, globally (Carley et al., 2017), in Germany (Hitaj & Löschel,

2019) and, sometimes, over-capacity in wind power technology in China (Dong et al., 2018; Luo et al., 2018; Xia et al., 2020).

Broadly, two design categories, namely, market-independent and market-dependent models, are discussed in literature (Couture & Gagnon, 2010; Ramli & Twaha, 2015). The distinguishing features between the two categories are based on whether payoff is fixed, adjustable for inflation (market-independent) or related to the electricity spot price (market-dependent) . The main four market independent models include; fixed price FIT design model, fixed price FIT policy with full or partial inflation adjustment, front-end loaded tariff model, and spot market gap FIT model (Ramli & Twaha, 2015). In contrast, market-dependent FIT policies require that renewable energy developers provide their electricity to the market, effectively competing with other suppliers to meet market demand (Couture & Gagnon, 2010; Mendonça, 2012).

Global distributional of impacts from REFITs

In similar vein, studies have also shown mixed results on the distributional impacts of REFIT largely influenced by tariff design and general economic conditions. Broadly, there is widespread criticisms of REFITs for having adverse consequences on welfare. For example, Winter and Schlesewsky (2019), Grösche and Schröder (2014) and Böhringer et al. (2022) concluded that Germany's feed-in tariffs are increasingly flowing into higher-income households because PV systems are more prevalent in these households and are therefore regressive.

Böhringer et al. (2022) went a step further to identify the possibility of abatement in the distributional impacts of REFITs using exemptions from electricity for residential consumers. Also, in the Philippines, REFITs have led to consumer welfare losses (Lagac & Yap, 2020). Apart from the distributional impacts, Yu et al. (2021) further found that inefficient REFIT setting worsened resource allocation in China's wind power industry between 2000 and 2013.

Impacts of REFITs in Africa

In Africa, adverse welfare impacts have brought many REFIT policies to abrupt end. The Government of South Africa introduced REFITs in early 2009 but abandoned it before its implementation in 2011 in favour of competitive procurement process (Meyer-Renschhausen, 2013). Ghana has replaced its REFIT policy in 2020 with competitive procurement mechanisms in the amended Renewable Energy Act, 2020, after less than a decade of implementation (Acheampong et al., 2021). After a very short while, almost all countries in Africa that had adopted REFITs have either transitioned or intending to transition to competitive procurement frameworks (IRENA, 2022).

In Ghana's case, the country initially enacted a REFIT policy in 2011 (Renewable Energy Act 2011, Act 832) and gazetted in 2013 which was for a period of 10-years (Ahiataku-Togobo, 2016). But In 2016, Ghana improved its strategy, increasing the contract limit to 20 years and relaxing capacity constraints (IRENA, 2022). Although, the initiative brought about 144 MW of installed capacity of all renewable technologies combined between 2013 and 2020 (Ghana Energy Commission, 2022), high electricity costs and prices due to unsolicited and negotiated PPAs which lead to overcapacity system fuelled the modification of the policy in 2020.

Synthesis of empirical literature

From the foregoing, a synthesis of surveyed literature that links identified research gaps to the novelty of analysis in this study is provided in Table *1*.

Table 1: Synthesis of surveyed empirical literature

Author(s) & Year	Focus of Research	Finding/Conclusion	Gap Identified	Modification	Justification
Coffman et al (2023)	Using a CGE framework, simulated carbon tax policy scenarios over a baseline Renewable Portfolio Standards (RPS) in Hawaii, USA	Found adverse impact of carbon tax on economic growth	(i) Modelled demand-side scenarios for energy. (ii) RPS mostly not applicable in developing markets like Ghana. (iii) low detail of economic structure due to high aggregation for countries in the GE framework	(i) Modelled scenarios for the supply-side of electricity. (ii) applied high data resolution of Ghana’s economic structure based on detailed SAM	Carbon tax on power generation is most feasible option with trickling effects to the end-user. Endline effects are captured with high detailed SAM for Ghana
Mier et al (2023)	Using a CGE framework, simulated carbon tax policy scenarios for the European electricity market till 2050	Higher electricity prices for consumers and higher rent for producers			
Arndt et al (2016)	Using a hybrid modelling approach, experimented three scenarios including carbon tax up to 2035 in South Africa	Carbon tax negatively affects electricity prices, employment and GDP	(i) Delinked source of pollution (fossil fuel) from electricity output as studies did not factor fossil fuel as input in the GE. (ii) Size/rapidity of tax is not considered (iii) Countries considered: China, South Africa,	(i) Fossil fuel is modelled as an input in power generation for Ghana (ii) Impact of rapid deployment of tax and cap measures are implemented	Fossil fuels are principal input-sources of pollution in power generation. Thus, a tax or cap policy ought to reflect through cost of input than on sales
Dissanayake et al (2020)	Simulated carbon tax, fuel tax and ETS on economic growth based on Indonesia’s NDCs using CGE				
Calderón et al (2016)	Analysed three scenarios in addition to a business-as-usual scenario for reducing				

	CO_2 emissions by 2050 in Colombia		Indonesia and Colombia are significant energy market players in terms of size and development than Ghana		
Xie et al. (2020)	Examined impacts of 10 decarbonization scenarios on GDP and household welfare in China up to 2030.				
Fremstad and Paul (2019); Steckel and Jakob (2021); Moz-Christofoletti and Pereda (2021); Känzig (2023);	Investigated effects of carbon tax on inequality	Carbon tax exacerbates inequality since low-income households spend a greater share of their income on carbon-intensive goods.	Possible biases in estimated results as studies did not account for full effects in a GE framework	Implemented a CGE framework	CGE accounts for full impact of policy measures through inter-sectorial linkages and economy-wide constraints
Ćorović et al (2022)	Examined decarbonization in the electricity market by limiting fossil fuel to electricity generating facilities	Limiting fossil fuel results in reduced electricity supply and higher tariffs.	Did not estimate impact on growth and consumer welfare	Computed the impacts on economic growth and consumer welfare	Feasibility of a policy measure is critically affected by impacts on growth and welfare
Winter and Schlesewsky (2019), Grösche and Schröder (2014) and Böhringer et al. (2022)	Examined effects of Feed-in tariffs on inequality	Feed-in tariffs are increasingly regressive	(i) Analyses are focused on 'prosumers' of electricity. (ii) jurisdictions for the studies including Germany and China, are heavily industrialised	Considered a utility scale approach, applying REFITs to Ghana's developing electricity market	A 'prosumer' case of REFIT is yet not realised for residential consumers in Ghana
Yu et al. (2021)	Assessed resource allocation in China's wind power industry between 2000 and 2013	REFITs worsen resource allocation			

			and have developed electricity markets		

Source: Nkrumah (2024)

Table 1 describes the author(s) and year of studies, mostly in the last 5 years, the primary focus of the research, and its findings. Afterwards, the identified gaps are presented for a block of studies with similar focus. These gaps are resolved through specific modifications in the present study with justifications.

Chapter Summary

In this review, the author has provided a critique of the general equilibrium theory that equilibrates sets of prices and consumption bundles across multiple products and inputs markets. This leads to aggregate measurements of outputs of goods and services, which in turn leads to measuring aggregate incomes, employment, and welfare. Special dispensation was given to the discussion of neoclassical production functions for the product market as basis for input-quality adjustment, production tax or subsidy – suggested pathways to decarbonization in the electricity sector. The general equilibrium analysis is implemented using well-known computable general equilibrium (CGE) mathematical models in GAMS and GEMPACK modules. Like the general equilibrium framework, CGE models account for multiple rebound effects from interlinked products and inputs in neoclassical market arrangements.

The empirical studies surveyed so far on the effects of decarbonisation through policies such as carbon taxation, fossil fuel restrictions or renewable energy feed-in-tariffs can be best described as almost reaching consensus on the effectiveness on reducing carbon emissions. The disagreement in literature, however, regards the extent of reduction in emissions by such policies, especially in meeting the global targets enshrined in the Paris

Agreement. As a result, scholars like Rosenbloom et al. (2020) suggest non-market mechanisms in order to guarantee global emissions reduction targets. On the other hand, the emerging theme in the extant literature has been that price-focused policies as discussed have adverse impact on growth and welfare unless accompanied by revenue redistribution to households.

CHAPTER THREE

RESEARCH METHODS

This third chapter discusses the research methods implemented to achieve aim and the three specific objectives set at the beginning of this research. This chapter begins by reviewing the research paradigms, designs, and methodologies relating to three research approaches in a spectrum: quantitative, qualitative, and mixed methods. The review thus enables the choice of an appropriate approach for this study. Following from the selection of an appropriate study approach, the chapter then discusses the specific design and methods adopted for the study, including the conceptual framework, analytical techniques, theoretical models, data sources and model calibrations.

Research Paradigms

A research paradigm describes the intuitive approach adopted to carry out the study. It constitutes the overall plan to conduct the research based on the researcher's worldview: a shared knowledge and understanding of what constitutes reality, how it is construed and uncovered (Madill & Gough, 2016). Authors like Khan, 2014 predicate research paradigm on 'basic belief systems' of the researcher involving conceptualisation of truth or reality and processes by which truth is discovered through an identified methodology that distinguishes between objectives beliefs and the opinion of the researcher. Three different paradigms are mostly covered in literature. They include quantitative, qualitative and mixed-method paradigms (Creswell & Creswell, 2018).

The quantitative paradigm of research involves hypothesis testing using numerical data and statistical procedures. The approach involves a deployment of a deductive procedure to confirming or rejecting an existing theory in a target population. Qualitative paradigm, on the other hand, involves an exploration and understanding of social and human problems through participatory data gathering with research participants about their feelings, knowledge and perceptions around a phenomenon which are not directly measurable in numerical terms. The researcher then places value-judgements and inductively interprets research findings from studied-participants unto a general case. Finally, the intersection of the two paradigms becomes the mixed method paradigm. It is a pragmatic approach to research other than a pendulum-swing between quantitative and qualitative paradigms and, therefore, involves a blend of the two sides of the spectrum. It is able to draw on the advantages of the two paradigms to overcome the weaknesses of the other.

It is worthy of emphasis that the stated research paradigms are underpinned by the researcher's worldviews that in turn influenced by philosophical roots in ontology (nature of reality) and epistemology (how we know what we know). A researcher's worldview refers to a philosophical stance based on the assumption of how reality is constructed (ontology) either as a singular and objective truth or multiple and socially constructed truth, and whether or not this reality can be known independently of the researcher (epistemology). Paradigms identified in the extant literature include positivism, constructivism, transformative, and pragmatism worldviews.

Other worldviews elsewhere identified include Critical Theory, and Participatory worldviews (Ramalho et al., 2015) . Positivism is belief that truth or reality can be objectively known outside the researcher's manipulation and can be verified using scientific and systematic inquiry. It holds a deterministic view of cause and effect between phenomena understudied. This worldview leans much towards the quantitative research paradigm This has been the most favoured paradigm in scientific literature used in studying the behaviour of natural objects usually in a controlled environment including scientific laboratories.

Most critics, however, argue against the effectiveness of this paradigm in a human and social setting, often in an uncontrolled environment. Overcoming the weaknesses of the positivists' worldview, a more recent evolution – post-positivism emerged around the 20th century that sought to apply scientific inquiry to human settings by, first, acknowledging researcher biases and margins of error in any measured reality. Post-positivism thus postulates that by minimizing biases and errors, a scientific inquiry can carefully be applied to observe and study the behaviour of individuals (Creswell & Creswell, 2018).

Alternatively, proponents of Constructivism, Transformative, Critical Theory and Participatory viewpoints, among others, believe that reality is constructed in a social setting; it is multiple, relative and subjective. This class of philosophies allows for active involvement of the researcher with the research participants and permits value-judgements and interpretations by the researcher on the data gathered from the participants. The qualitative research paradigm thus suits these worldviews. It is profitable for unravelling the deepseated experiences and knowledge of research participants that would otherwise not be determined using quantitative scales. It is suited for studies in history, ethnography, case studies, among others. The reality exhumed by this paradigm is however not replicable with different participants since experiences are subjective and limited to specified context.

It is the last philosophical standpoint, pragmatism, that combines the extreme objective-subjective worldviews into a blend of worldviews about reality. Maxwell, 2016 and Creswell (2011); Creswell and Tashakkori (2007) have argued vehemently that there are sometimes overlaps in the two worldviews. This thus affords a workable plan that draws on the advantages of the worldviews sitting at the ends of the knowledge spectrum, particularly the weaknesses inherent in the positivist ideas. It is in this light that the mixed method paradigm marries quantitative and qualitative research paradigms in a framework that is practical and workable for an inquiry. It is worthy to state at this point that the study which seeks to analyse the behaviour of rational economic agents to climate-mitigation policies in the electricity industry, appropriately aligns with the positivists philosophy.

Research Design

Following from research paradigms, designs are stylised blueprints for actual implementation of the research. It is a detailed presentation of procedures for undertaking the study (Kumar, 2011). Kerlinger (1986) also defines a research design as a complete scheme of the study from hypothesis formulation to analysis of findings. The purpose of a design is to provide stepwise guidance to the research process, including tools required to achieve the aim of the study (Kumar, 2011). A number of designs for quantitative, qualitative and mixed-method paradigms abound in literature. So, at any material moment, a researcher must choose the most appropriate design that resonates with their stated worldviews to enable and guide the research process from conceptualisation to analysis of results.

Common research designs under the quantitative paradigm can be grouped into experimental, quasi-experimental and non-experimental designs. Experimental designs, also referred to as randomized-control trials, follow the steps of true experiments in which treatment is applied to a randomized treatment group and the aftermath results compared with a with a randomized control group, except that the latter take place in a controlled environment like the scientific laboratory. A key feature of research participants in the true experiments is that they ought to be homogenous and randomized. Quasi-experimental designs, on the other hand, are less rigorous on randomisation of treatment and control groups but retains, to large extent, an experiment with a treatment group. Often, cause-effect relationships are established from the same treatment group monitored at different times or space. Examples include before-and-after experiments, matching experiments, repeated sample studies, cohort studies, longitudinal studies, and so on.

Finally, non-experimental designs of the quantitative paradigm seek to explain and make inferences about the causal and correlational relationships between two or more phenomena that have already happened. Periodic (time series) or one-time (surveys and census) data are often collected and analysed using statistical techniques to unravel the relationships among variables in the data. Sometimes, inferences drawn from the data could permit projections and forecasts into the future based on the established relationships within the data.

Examples of non-experimental designs include, inter alia, surveys, trends studies, optimisation, and simulation studies.

This study uses optimisation and simulation framework of the non-experimental experimental design to understand the optimal behaviour of economic agents to specified climate-mitigation policies in the electricity sector and the associated full-equilibrium impacts across all markets in the domestic economy. In essence, all economic agents in a domestic economy would have to optimise their supply and demand choices in response to a policy shock in the electricity sector. This conceptualisation outrightly fails the strict proof of a randomized design which would require a set of homogenous domestic economies randomised into treatment and control cohorts. It is a fact that, no two countries are the same or homogenous. Hence, true experiment breaks down, likewise quasi-experimental design which would also require a 'matched' comparative group or at least a repeated study design. Notwithstanding, optimisation and simulation models are founded on iterated loops that perform several repeated iterations of economic values, and when convergent, they produce optimal results similar to repeated trials in quasi-experiments.

Theoretical Model

This section provides a detailed description of the theoretical model employed for the study including medium-term assertions that emissions capping and carbon taxes reduce thermal electricity generations and decreases economic welfare, and feed-in-tariffs increasing solar penetration and reducing consumer welfare (poverty and inequality). Two related techniques are implemented. For the first and second objectives, the study adopts a computable general equilibrium (CGE) framework whereas a financial microsimulation is used for the third and final objective.

Computable General Equilibrium (CGE) Model

The CGE framework explains how supply and demand in an economy with many markets interact to culminate in an equilibrium of prices. In the general equilibrium framework, all economic agents optimize their objective functions and are in equilibrium (Debreu, 1982). The notable Computable General Equilibrium (CGE) models which are based on the Walrasian general equilibrium framework have since been applied to study the economy-wide and, in some cases, regional impacts of changes in economic decisions and exogeneous shocks. The extensive experimentation with computable general equilibrium (CGE) models in the past half-a-century has been instrumental in generating a greater degree of understanding broad policy issues.

Analysis of emissions reduction based on general equilibrium framework can examine the impacts of broad policy changes and macro shocks on all sectors, markets and economic players (**Figure 5**). CGE models specify all their economic relationships to predict the change in policy variables and measure the economic impacts at a given level of technology and consumer preferences. The interaction of various markets and flow of physical goods and financial resources among agents in the economy.

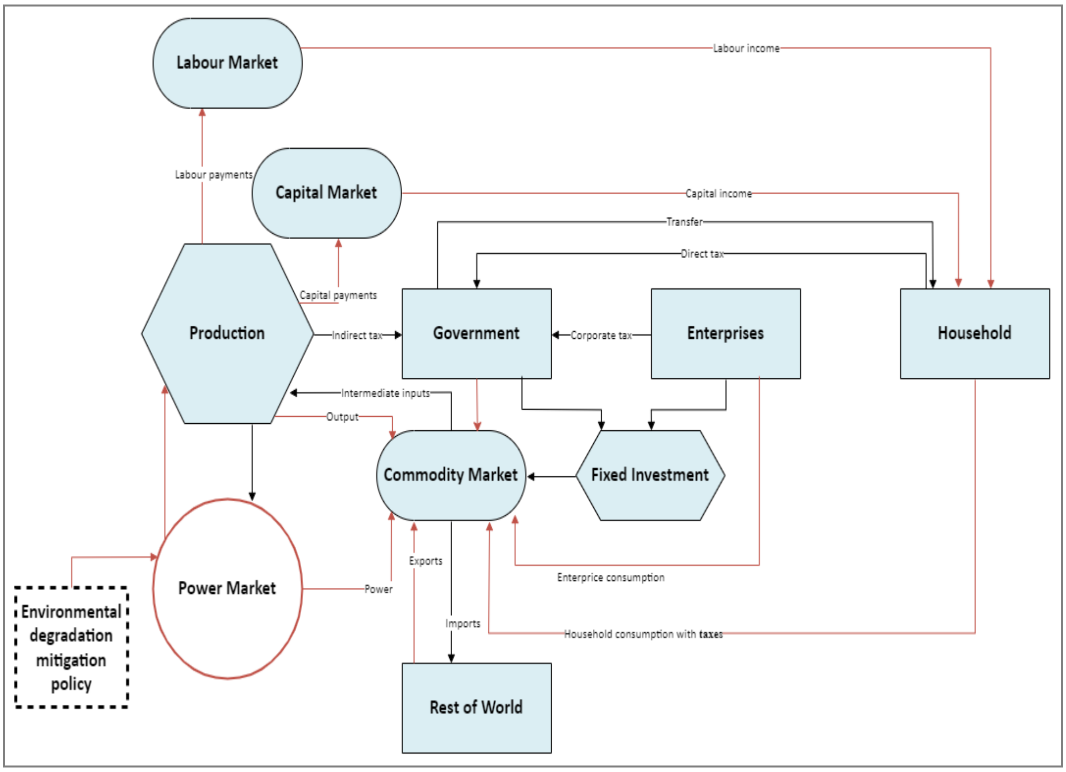

Figure 5: A CGE Model with an Exogenous Environmental Policy
Source: Nkrumah (2024)

Thus, a general equilibrium model considers interaction of various markets and flow of physical goods and financial resources based on an exogenous policy (Kilkenny & Robinson, 1990; S. Robinson, 1991). The ripple effect is felt through production activities which churns out physical goods into the commodity market, as well as financial payments to factors of production and to the commodity accounts, and final GDP estimates. The rest of the agents and markets interact iteratively to achieve an equilibrium in prices in all markets.

Model specification

This section presents mathematical description of relevant behaviour of key economic agents in a small open economy, and how they interact to be in equilibrium. The economic agents are typically producers, consumers, government, private investment activities, and rest of the world. In what follows, the salient characteristics and behaviours of economic agents are discussed while the full mathematical equations and parameters are provided at the appendix of this thesis.

Producer behaviour

The study adopts a relatively broad and nested production technology, KLEMS (Capital (K), Labour (L), Energy E, physical Material inputs (M), and Services inputs (S)), used in the production of most economic goods and services. As shown in **Figure *6***, the permutation of the elasticity of substitution in the nested function, however, is KE-L-MS where capital and energy are first combined by a Leontief production technology into a composite input (KE). The composite input KE is in turn combined with labour (L) and aggregate intermediate inputs (MS) using a CES technology. Individual intermediate inputs from domestic and import sources are, nonetheless, transformed into aggregate inputs using a Leontief production technology.

In the first place, the typical producer within the economy is assumed to be risk-averse who maximizes profit with a given set of inputs (capital (K), labour (L), Energy (E) and aggregate intermediate inputs (M)) and electricity prices, at a given innovation (A), in a nested CES function. Lofgren et al (2002), and Robinson and Lofgren, (2005) state production function given as

$$q = \Lambda \left(\sum_{f} a_{if} V_{if}^{-\rho_i} \right)^{-\frac{1}{\rho_i}}, f \in F \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . (1)$$

Where q is the output quantity of sector i, Λ is a shift parameter representing autonomous technical change (total factor productivity, (TFP)).

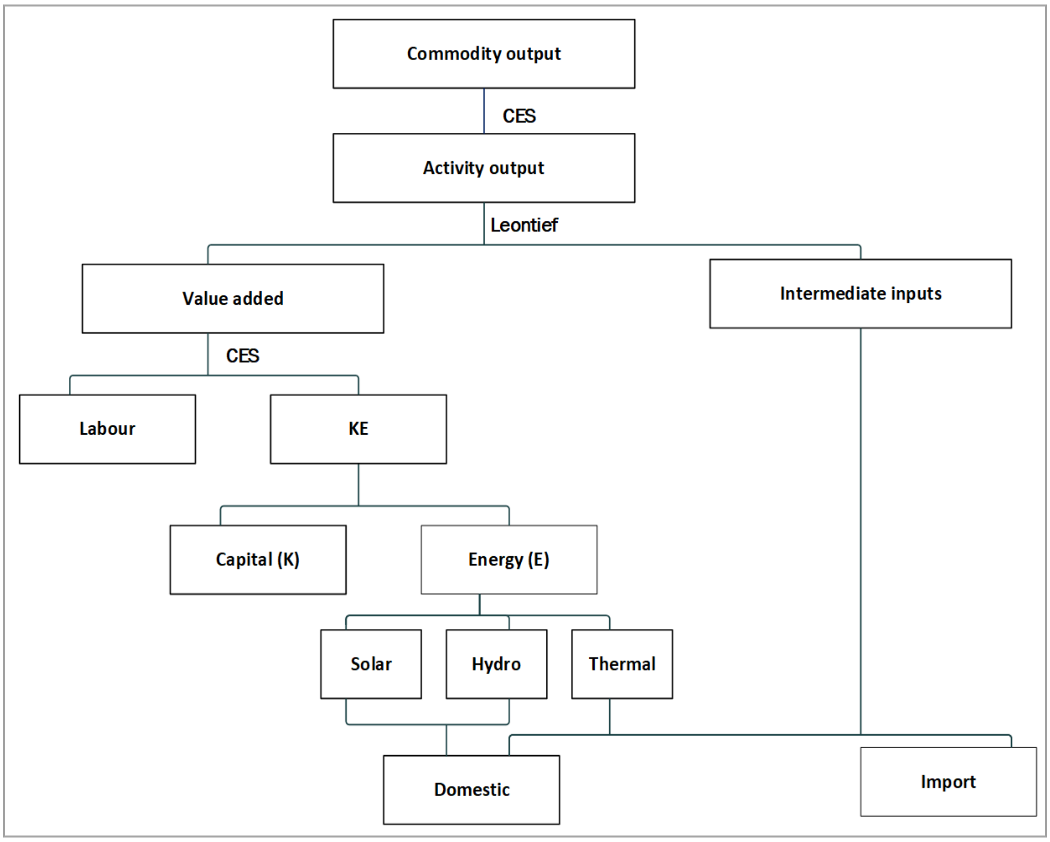

Figure 6: Production Technology
Source: Adapted from (Robinson & Lofgren, 2005)

Also, V represents quantity demand of each factor of the set, F: capital, labour, and energy. The parameter ρ measures the level of substitution between the factors such that the elasticity of substitution, $\sigma = 1/(1+\rho)$. The CES production function allows for a range of substitution possibilities between factors in response to relative price changes.

By inspection, the production function in (7) is affected by demand and level of substitution for emissions-associated energy inputs and is akin to the income function in (6). If level of substitution between factors becomes large, then the effect on final output also becomes minimal. The reverse is also true. Further, the author assumes the energy market to be initially competitive until a quantity restriction is placed on energy to mitigate GHG emissions from production activities. Hence, producers earn monopoly rent on outputs whose inputs are restricted by carbon mitigation policies, in this case, electricity.

Profit, π, in sector i defined as the net of revenues and factor payments is also given as:

$$\pi = \mathrm{p_i q_i} - \sum_{f} (w_f\, v_{if}) \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\,(2)$$

Where $\mathrm{p_i}$ is price of value-added, and W_f is payments to factors of production. Hence, to maximise profits subject to outputs constraint in (1), equations (2) and (1) are solved using the Lagrange equation system. The demand for factors of production (v) relative to changes in the prices of other factors (w_f) becomes:

$$v_{if} = \Lambda^{-\frac{\rho_i}{1+\rho_i}}\, \mathrm{q_i} \left(a_{if}\, \frac{p_i}{w_f}\right)^{1/(1+\rho_i)} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\,(3)$$

Thus, demand for factor inputs depends on prices of composite factors (W_f) and the level of substitution, (ρ), between factors of production. The composite factor energy input, (H), which is an aggregation of energy sources is derived by

$$\mathrm{H}_{if} = \sum_{f} \delta \mathrm{H}_{ifd} = \sum_{f} \delta \left(\Lambda^{-\frac{\rho_i}{1+\rho_i}}\, \mathrm{q_i} \left(a_{if}\, \frac{p_i}{w_{fd}}\right)^{1/(1+\rho_i)} \right) \ldots\ldots\ldots\ldots\ldots.\,(4)$$

Where p_i is price of aggregate energy to produce commodity i, and δ is shares of disaggregated energy source inputs (with subscript fd).

Demand for aggregate intermediate inputs, on the other hand, used in the production process are determined by their fixed input-output coefficients (X_{ij}) and prices of inputs from other sectors, (p_j). The producer price function is thus:

$$p_{ij} = \mathrm{p_i} + \sum_{j} p_j X_{ij} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . (5)$$

It is important to mention that equation (5) highlights the possible interindustry linkages through competition for similar factors and supply of intermediate inputs among sectors. These production linkages are best captured by a general equilibrium model that accounts for the use of both factors and intermediates in the production process.

Consumer behaviour

The Stone-Geary utility function is an extension of the Cobb-Douglas function that incorporates minimum (or subsistence) levels of consumption (Deaton & Muellbauer, 1980). This is given as:

$$u(x_1, x_2, \ldots, x_n) = \prod_{j=1}^{n} (x_j - z_j)^{a_j} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . . (6)$$

Where $z_j \geq 0$ are subsistence levels of consumption and a_j nonnegative weights that add up to 1. The utility maximization problem under the budget constraint imposed by income level m and prices p_j and given minimum consumption z_j is:

$$Max \ \ u(x_1, x_2, \ldots, x_n) = \prod_{j=1}^{n} (x_j - z_j)^{a_j} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . (7)$$

Subject to

$$\sum_{j=1}^{n} p_j x_j = m \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . \ldots\ldots . (8)$$

By solving this problem yields linear expenditure function

$$p_j x_j = p_j z_j + a_j (m - \sum p_i z_i) \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Government activity

Government activities in a typical CGE model are mainly about revenue mobilisation through taxes and other domestic and foreign receipts and spending both domestic and abroad. Total domestic revenues, R is the sum of all taxes:

$$R = \sum_i (tc_i p_i q_i + tm_i pwm_i M_i + te_i pwe_i E_i) + \sum_h (ty_h Y_h) + \sum_f (tf_f w_f \bar{S}_f) \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (10)$$

Where M is imports, E is exports, Y is income and S is factor supply. Also, tc is consumption tax rate on good i, tm and pwm are, respectively, import tariff and world price of import; te and pwe are export tariff and world export price, respectively; ty is income tax rate, and tf is factor income tax rate. Taxes are mostly exogenous in CGE models allowing for policy simulations on different tax designs and rates.

The government consumes its revenues on purchase of goods and services and savings through gross fixed capital investments. The balancing equation for government revenues (R) and expenditures is given as:

$$\mathrm{R} = G + FB \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots . (11)$$

Where G is government consumption expenditure, and FB is the recurrent fiscal balance. Revenues are bolstered through economic growth and incomes from abroad that allow increased investments in the provision of public goods and promotion of productivity in economic production by the private sector.

Investment and savings

The level of investment demand for goods and services (*N*) is defined to be equal to investible funds in the economy. The total value of all investment is therefore equal to the sum of the value shares of investible funds (I) for each good and service in the economy:

$$\mathrm{I}\,\epsilon_i = p_i N_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

Where ϵ is the value share for each investment good, and p is the equilibrium market price for each good. The level of investible funds (I) is determined by the macroeconomic closures imposed on the CGE model. This will be dealt with in the next section.

Rest of the world

The energy transition is a concert of global efforts of individual countries, regions and continents to mitigating the impacts of climate change by switching from fossil-based fuels to renewable energy sources to promote economic prosperity and preserve the natural environments of countries and the world. The interdependence of countries, especially developing countries on inflows and outflows of merchandized goods and services, capital, financial and technology transfers are crucial to the transition agenda in these countries. It, therefore, makes sense to assume an open economy, doing away a complete autarky situation for any specific case country.

Theoretically, international trade occurs when there is no equilibrium between domestic supply and demand. It is taken for granted that in situations of excess supply of goods and services over demand, export occurs. Likewise, a shortage in supply will result in imports from abroad. More precisely, Armington (1969) postulated a two-way international trade inflow based on an imperfect substitution between domestically produced and imported products. Armington's approach has become the gold-standard in CGE modelling to capture international trade with foreign markets.

In the same way, this thesis also adopts an imperfect substitution in a CES function between domestically produced and imported goods.

$$\mathrm{q_i} = \Omega[\,\mu_i D_i^{-\theta_i} + (1+\mu_i) M_i^{-\frac{1}{\theta_i}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(13)$$

$$(1 - tc_i) p_i\, \mathrm{q_i} = p_{di} D_i + p_{mi} M_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(14)$$

$$p_{mi} = (1 + tm_i) pwm_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(15)$$

Where θ_i is the substitution between imported quantities and domestically produced quantities transformed into a composite product Q. Also, μ_i is the share parameter for domestically produced good D_i in q at domestic price p_{di}, whereas M are imported quantities of the goods supplied to domestic market, Ω is the shift parameter, tc is an indirect sales tax, tm is the import tariff rate, and pwm is the world import price. As shown in Equation (15), import price p_{mi} is determined by an exogenous world price, pwm_i.

To determine the level of imports, we maximize $p_i q_i - p_{di} D_i - p_{mi} M_i$, subject to Equation (19). By rearranging first-order condition gives the following:

$$\frac{D_i}{M_i} = \left(\frac{\mu_i}{1-\mu_i} \frac{p_{mi}}{p_{di}} \right)^{\frac{1}{(1-\theta_i)}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(16)$$

Analogous to import CES function, exports are assumed to have imperfect substitution between products in the domestic and foreign markets, captured in a constant elasticity of transformation (CET):

$$\mathrm{X_i} = \Gamma_i \left[\, \tau_i D_i^{-\varphi_i} + (1+\tau_i) E_i^{\varphi_i} \right]^{\frac{1}{\varphi_i}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(17)$$

$$p_i X_i = p_{di} D_i + p_{ei} E_i \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (18)$$

$$p_{ei} = (1 + te_i) pwe_i \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (19)$$

Where φ_i is the substitution relationship between exported quantities and domestically produced quantities of X_i, while E_i is exported quantities of X_i. Also, te is export tax rate, and pwe is the exogenous world export price.

By solving $p_i X_i - p_{di} D_i - p_{ei} E_i$ subject to Equation (19) gives the level of imports and exports for each product as:

$$\frac{D_i}{E_i} = \left(\frac{\tau_i}{1 - \tau_i} \frac{p_{di_i}}{p_{ei}} \right)^{\frac{1}{(\varphi_i - 1)}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (20)$$

Worthy of mention that the elasticities of substitution between goods in the domestic and foreign markets in international trade (θ and φ) in (16) and (20) are taken from global estimates from empirical literature.

Equilibrium condition

Prices in general equilibrium models are determined by the equilibrium conditions in the product market and factor markets which set economic agents (producers, households, government, rest of world) up to be in equilibrium through participation in the various markets. The product market is cleared by domestic prices (p_{di}) in the general equilibrium:

$$Q_i = C_i + N_i + G_i + X_i - M_i \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (21)$$

Where Q is composite supply quantity, C is private consumption, N is private investment demand, G is government consumption expenditure, X is export, and M is import. The sum of the right-hand side variables constitutes aggregate demand.

On the other hand, the factor market is cleared by the price of factor (w_f) that equates:

$$\sum_{i} v_{if} = \bar{S_f} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (22)$$

Where $\bar{S_f}$ is the total factor supply and v_{if} is the factor demand in each sector. Total factor supply is often fixed in a given year. Thus, factor supply is considered exogenous in the general equilibrium framework.

Related to the factor market is the assumption regarding the ownership of factors of production. The most common and simplest assumption in many CGE models is to assume household ownership of factors of products. Thus, individual households receive factor payments which equal total household incomes:

$$Y_h = \sum_{if} \delta_{hf}(1 - tf_f)w_f v_{if} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (23)$$

Where δ is factor income shares for individual households determined by total factor endowment for each household, tf_f is direct tax rate on total factor earnings, $w_f v_{if}$.

Model closure rules

Closure of CGE models is a contentious topic with a large literature following Amartya Sen's criticism of 'overdetermination' in macroeconomic and in general equilibrium models (Rattsø, 1982). This has led to close examination of macroeconomic underpinnings applied to most CGE models at the time (S. Robinson, 2006). The extensive survey of CGE models by Rattsø (1982), Robinson (1991) and Taylor (1990) have contributed to the general consensus in the extant literature CGE model solutions depend on the adopted model closure rules. According to Rattsø (1982), the study by Taylor and

Lysy (1979) revealed that the model closure, which often taken for granted, to a great extent determined the model's qualitative characteristics.

These closure rules regard the modeler's choice on variables that become exogenous and endogenous in the model (Decaluwé & Martens, 1988; Kilkenny & Robinson, 1990; Taylor & Lysy, 1979). These decisions are made by the builder to ensure model convergence due to the absence of financial/monetary signals like interest rates in the real economy often found in CGE models (Rattsø, 1982). However, in selecting which macro-closures, modelers often consider closures that best mimics the economy being modelled in real-world (Lofgren et al., 2002). Other scholars, nonetheless, argue for a 'neutral' closing of the model whereas others prefer to select closures that highlight economic and political considerations of the delimited economy (Rattsø, 1982).

In the IFPRI standard CGE model by Lofgren et al. (2002), macro-closures are presented in the form of three macroeconomic balances; factor market employment and mobility; and choice of a numeraire (

Table 2). The macroeconomic balances are the Savings– Investment balance, government account balance, and the foreign savings (current account balance). In each macro-balance, there are multiples of possible macro-closures that give consistent results independent of choice of closure in the other two macro-balances (Lofgren et al., 2002). However, the choice of a numeraire and behaviour of the factor market are, altogether with closures within the macroeconomic balance, provide varied but consistent results based on the modeler's perspective of the economy. Each model closure (see,

Table *2*) with its implications is briefly presented in the following paragraphs.

Savings–investment closure (SICLOS)

Often, CGE models are abstracts of the real economy without financial and monetary market signals like interest rates (Decaluwé & Martens, 1988; Kilkenny & Robinson, 1990). Hence, the Savings-Investment closure fills this vacuum in order to establish equilibrium between aggregate savings and aggregate investment after an economic shock (S. Robinson, 1991, 2006). In the abounding literature, the Savings–Investment closures are either savings-driven (investment adjusts endogenously) or investment driven (savings rate is endogenous). Yet, in IFPRI's standard model, Lofgren et al. (2002) adds the so-called 'balanced closures' with proportional or scaled adjustments in the components on absorption.

The first closure under the Savings-Investment balance, SICLOS-1, is an investment-driven closure in which real private capital formation is fixed. Therefore, following a shock, aggregate savings adjusts among private institutions by the same number of percentage points to equilibrate the change in investment. By this, private savings in the base-year is able to adjust by equal proportion to the change in investment. The next closure, SICLOS-2 is also investment-driven, except that the adjustment in private savings is multiplied by a scaler (Lofgren et al., 2002). The implication of these two closures is equality of aggregate savings with investment. However, the distribution of impacts on private institutions could be wide-ranging. On the other hand, the second alternative closure, SICLOS-3, is savings-driven in which private savings are fixed and private investments adjusts by a scaler to equilibrate aggregate investment with global savings (Rattsø, 1982; S. Robinson, 1991; Taylor & Lysy, 1979).

The last two alternative closures, SICLOS-4 and SICLOS-5, are variants of the investment-driven closures, SICLOS-1 and SICLOS-2, respectively, such that adjustments in absorption are spread across all of its components: household consumption, investment and government consumption. According to Lofgren et al. (2002), these closure differ from their earlier versions in the sense that in SICLOS-1 and SICLOS-2, both investment and government consumption are fixed. Hence, household consumption becomes the only adjustable component of absorption. These closures present a moderate savings adjustment in the components of absorption compared to the extreme case of huge adjustments in only household consumption.

Table 2: Macroeconomic closures in the IFPRI Standard Model

Model constraint				
Savings–Investment Closure (SICLOS)	**Government Closure (GOVCLOS)**	**Rest of the World Closure (ROWCLOS)**	**Numeraire (NUMCLOS)**	**Factor Employment and Mobility**
SICLOS-1 Fixed capital formation; uniform MPS point change for selected institutions	GOVCLOS-1: Flexible government savings; fixed direct tax rates	ROWCLOS-1 Fixed foreign savings; flexible real exchange rate	NUMCLOS 1: Consumer Price Index (CPI) is numeraire (and fixed) – Producer Price Index (DPI) is flexible	FMOBFE: Factor is fully employed and mobile between activities
SICLOS-2: Fixed capital formation; scaled MPS for selected institutions	GOVCLOS-2 Fixed government savings; uniform tax rate point change	ROWCLOS-2: Flexible foreign savings; fixed real exchange rate	NUMCLOS 2: Producer Price Index (DPI) is numeraire (and fixed) – Consumer Price Index (CPI) is flexible	FACTFE: Factor is fully employed and activity specific
SICLOS-3: Flexible capital formation; fixed MPS for all non-government institutions	GOVCLOS-3: Fixed government savings; scaled direct tax rates for selected institutions			FMOBUE: Factor is unemployed and mobile between activities
SICLOS-4: Fixed investment and government consumption absorption shares (flexible quantities)				
SICLOS-5: Fixed investment and government consumption absorption shares (flexible quantities); scaled MPS for selected institutions				

Source: Lofgren et al. (2002)

Government balance closure (GOVCLOS)

The government balance closure determines the way the government reacts to changes in its budget position. The government balance, also known as government savings, is the net of current government revenues and current government expenditures. So, in

Table 2, the first closure, GOVCLOS-1, indicates that government savings is a flexible residual while all tax rates are fixed (Lofgren et al., 2002). That is, when the government's budget position shifts due to changes in tax revenue and spending, government savings endogenously adjusts to restore equilibrium between revenue and expenditure. However, under GOVCLOS-2 and GOVCLOS-3, the base-year direct tax rates of private institution are adjusted endogenously to generate a fixed level of government savings either by the same number of percentage points (GOVCLOS-1) or multiplied by a flexible scaler (GOVCLOS-2).

Rest of the world closure (ROWCLOS)

An open economy with interest rate signals is able to allocate resources between the domestic and the external economies. Thus, without interest rates, the rest of the world closure for the external balance is in two folds. The first, ROWCLOS-1, fixes foreign savings and endogenously adjusts the real exchange rate (S. Robinson, 1991, 2006; Taylor, 1990). In this regard, a shortfall, for instance, in the exogenous foreign saving at fixed world prices, all other things remaining constant, will to a depreciation of the real exchange rate that will also reduce imports and increase exports (Lofgren et al., 2002). This closure typically analyses the reaction of domestic efforts through trade with the rest of the world like import substitution, export promotion, among others, other than resorting to unlimited borrowing, grants and remittances from external sources. The second alternative closure, ROWCLOS-2, the real exchange rate is fixed while foreign savings is flexible (Kilkenny & Robinson, 1990). Accordingly, the real exchange rate is indexed to the numeraire (Lofgren et al., 2002).

Numeraire (NUMCLOS)

The IFPRI model sets up the price level as the numeraire. Unlike the classic Keynesian proposition that set wages as the numeraire, neo-Keynesian and structuralist economists also set the general price level as numeraire while wages is the equilibrating macro variable (Rattsø, 1982; S. Robinson, 2006; S. Robinson & Lofgren, 2005). Under the first closure, NUMCLOS-1 sets up the consumer price index (CPI) as the numeraire and therefore fixed. That means, adjustments in prices in the domestic economic are indexed to the consumer price. On the other hand, NUMCLOS-2 sets the producer price index (DPI) as the numeraire. In that case, the price paid by the producer becomes the yardstick against which all prices in the domestic economy are measured.

Factor Employment and Mobility Rules

Finally, the IFPRI model presents three possible market behaviour governing employment and mobility of factors of production. In the first place, FMOBFE presents the case for full factor employment and mobility between sectors. In this instance, factor wages (broadly defined to include rents) is set as the market-clearing variable for each factor (S. Robinson, 2006; S. Robinson & Lofgren, 2005). The second factor market behaviour under FACTFE also describes full factor employment but, this time around, factor is activity specific. That is, factor is completely immobile across different sectors. Hence, only the wage (rent) distortion parameter adjusts to clear each factor market. The last, but not least, behaviour of the factor market is FMOBU in which factor is unemployed and completely mobile between sectors. In that regard, supply of factor is endogenous while wages and rents, and the wage distortionary parameter are all fixed.

The above model closures and factor market behaviour could be combined in several form to generate alternative model results underpinned by the modeler's beliefs regarding the historical operations of the economy and the policy issues at stake (Lofgren et al., 2002; Rattsø, 1982). Most often than not, the modeler's beliefs are influenced by theoretical considerations regarding income distribution as argued by Amartya Sen. Therefore, works by Rattsø (1982), Robinson (2006) and Taylor (1990) classified choices of macro closures based on the Neoclassical, Johansen, and the Keynesian/Structuralist traditions (see Table 3).The IFPRI model also presents a 'balanced closure' rules as midway between the Neoclassical and the Johansen rules. These are discussed in brief detail.

First, the Neoclassical closure rules are principally savings-driven investment (fixed savings and endogenous investment) with full employment of factors. Thus, in the IFPRI standard model, a neoclassical closure includes SICLOS-3, GOVCLOS-3, ROWCLOS 1, and FMOBFE or FACTFE. While other variants of the neoclassical closure exist based on different renditions of the government balance and the external balance closures, they principally based on the savings-driven investment closure and full employment of factors. The neoclassical closure assumes that the interplay between interest rate and investments occur outside the model. However, investment is able to adjust endogenously to equal global savings (Rattsø, 1982; S. Robinson, 2006). The neoclassical closure is ideal to assess the impact of shocks on capital formation and economic growth (Aslan & Altinoz, 2021).

On the other side, the Johansen closure rules following the postulations by economist Leif Johansen, assumes exogenous investment, full employment of factors, and endogenous tax rate (Rattsø, 1982; S. Robinson, 2006). So, in the Johansen rules, the role of savings and investment in the neoclassical closure rules are reversed, so that savings adjust endogenously through taxed consumption to re-establish equilibrium with investment. Put differently, by assuming an endogenous tax rate, t, private consumption is adjusted through changes in disposal income that matches changes in output and investment.

Table 3: Dominant classes of macro-closure rules

Macro Constraint	**Neoclassical**	**Johansen**	**Balanced**	**Keynesian/ Structuralist**
Savings–Investment	SICLOS-3: Savings-driven investment (Flexible capital formation; fixed MPS for all non-government institutions)	SICLOS-1: Investment-driven savings (Fixed capital formation; uniform MPS point change for selected institutions) SICLOS-2: Investment-driven savings (Fixed capital formation; scaled MPS)	SI-4: Fixed investment and government consumption absorption shares (flexible quantities); uniform MPS point change for selected institutions	SI-1: Fixed capital formation; fixed MPS for all non-government institutions
Government	GOVCLOS-1: Flexible government savings; fixed direct tax rates	GOVCLOS-1: Flexible government savings; fixed direct tax rates	GOVCLOS-1: Flexible government savings; fixed direct tax rates	GOVCLOS-1: Flexible government savings; fixed direct tax rates
Rest of the World	ROWCLOS 1: Fixed foreign savings; flexible real exchange rate	ROWCLOS 1: Fixed foreign savings; flexible real exchange rate	ROW 1: Fixed foreign savings; flexible real exchange rate	ROW 1: Fixed foreign savings; flexible real exchange rate
Factor Employment and Mobility	FMOBFE: Factor is fully employed and mobile between activities FACTFE: Factor is fully employed and activity specific	FMOBFE: Factor is fully employed and mobile between activities FACTFE: Factor is fully employed and activity specific	FMOBFE: Factor is fully employed and mobile between activities FACTFE: Factor is fully employed and activity specific	FMOBUE: Factor is unemployed and mobile between activities

Source: Lofgren et al (2002), and Diao and Thurlow (2012)

This closure, which is the default closure in the IFPRI model is distinguished from the neoclassical closure rules by switching to SICLOS-1 or SICLOS-2. It was the contention of Lofgren et al that the Johansen closure rules is ideal for exploring welfare changes of alternative policies in a static, and single-period models.

Nonetheless, both neoclassical and Johansen alternatives do not yield effects on aggregate GDP, inflation and employment. They only result in a redistribution of existing output through investment and consumption changes (S. Robinson, 2006). Hence, a Keynesian closure also known as the structuralist closure is able to affect GDP and employment through a Keynesian multiplier process. According to Taylor (1990), the structural characteristics of the economy are basic to its functioning. Thus, the structuralist consider several socioeconomic and political factors such as income distribution, market power, density of chains of production, ownership of factors of production, functioning of financial intermediaries, technical advancement, among others (Taylor, 1990; Taylor & Lysy, 1979). In relation to the IFPRI model, a structuralist closure assumes an investment-driven closure (exogenous investment) but with fixed MPS and with labour unemployment. The argument is, variations in the level of output and employment will make the savings and investment market clear (Rattsø, 1982; S. Robinson, 2006).

Notwithstanding, the study implements an alternative closure rule, the ‘balanced closures’, that lie between the extreme neoclassical and the Johansen (Lofgren et al., 2002). This almost follows the Johansen rules except that the MPS is spread across all components of absorption by the same number of percentage points. Lofgren et al (2002) argued that both the savings-driven neoclassical closure and the investment-driven Johansen closure seem extreme when looking at the historical experience of countries adjusting to macro shocks, and that it is useful to incorporate a balanced closure If the analysis aims at capturing the likely effects of an exogenous shock or policy change in a given historical, current, or future setting. Moreover, Lofgren et al argue that the balanced closure closely mimics the real world, with simultaneous adjustments in the three components of absorption.

Model Calibration

The model presented in this study is based on the International Food Policy Research Institute's (IFPRI) comparative-static model which is in the traditions of Lofgren et al (2002), and Robinson and Lofgren (2005). However, the IFPRI standard model is moderately tweaked to grossly suit the analysis set out in this study. Next, the model involved the compilation of a database that describes the Ghana's economy and is used to assign values to the parameters of the mathematical equations. This process is called the 'calibration' of the model.

Table 4: Entries in a macro-SAM

	Activities	Commodities	Factors	Enterprises	Households	Government	Taxes	Investment	Rest of the World	Total
Activities		Marketed outputs			Private non-marketed consumption					Activity income
Commodities	Intermediate demand	Transaction costs			Private marketed consumption	Government consumption		Gross capital formation	Exports	Total demand
Factors	Value-added								Foreign transfers to factors	Factor income
Enterprises			Factor income to enterprises			Government transfers to enterprises			Foreign transfers to enterprises	Enterprise income
Households			Factor income to households	Enterprise transfers to households		Government transfers to households			Foreign transfers to households	Household income
Government				Enterprise transfers to government	Household transfers to government		Taxes paid to government		Foreign transfers to government	Government income
Taxes	Taxes on producers	Taxes on products	Factor taxes	Corporate taxes	Household taxes					Tax income
Savings				Enterprise savings	Household savings	Government savings			Foreign savings	Savings
Rest of the World		Imports	Factor payments abroad	Enterprise payments abroad	Household payments abroad	Government payments abroad				Foreign exchange outflow
Total	Activity expenditures	Total supply	Factor expenditures	Enterprise expenditures	Household expenditures	Government expenditures	Tax payments	Investment	Foreign exchange inflow	

Source: Ghana Social Accounting Matrix report 2015

The most important database for CGE model calibration is a social accounting matrix (SAM). A SAM is a square matrix in which each account is represented by a row and a column (see Table 4). Each cell reflects a payment from the column account to the row account. By double-entry accounting principle, total receipts (row total) equal total payments (column total).

Macro SAMs are further disaggregated with nationally representative surveys and administrative data to obtain a SAM at the micro level. National SAMs are akin to the traditional Leontief input-output table (IOTs). The difference, however, lies with the inclusion of activities (i.e., production activities) in SAMs which are absent in IOTs. Otherwise, both frameworks capture monetary payments and receipts of goods and services in circular economy within a given period, usually a year. SAMs and IOTs are built on national supply and use tables, system of national accounts, and international trade accounts, among other national and international accounts.

Ghana's SAM, like any national SAM, is an economy-wide economic data matrix that captures the detailed economic structure of the country. The most recent SAM for Ghana is for 2015 which disaggregates receipts and payments on 55 production sectors, 56 commodities, 13 factors of production, income and expenditures of rural and urban households by quintile, the government budget, and the balance of payments (GSS et al., 2017). However, for parsimony and model efficiency the study aggregated the products and industries to about half of the number (i.e., 29 each; see Table 5). This is after the electricity industry has been split into its generation sources, that is, hydroelectricity, thermal and solar. This afforded much specificity on the effects of emissions control on various sources of electric power to the national grid as will be demonstrated in the subsequent chapters.

Table 5: Economic sectors used in the CGE model

No.	Agriculture	No.	Industry	No.	Services
1	Crop	5	Extraction of Crude oil	19	Wholesale and retail trade
2	Livestock	6	Other mining	20	Transportation and storage
3	Forestry	7	Food and beverage processing	21	Accommodation and food services
4	Fisheries	8	Textiles, clothing and leather	22	Information and communication
		9	Wood and paper	23	Finance and insurance
		10	Petroleum	24	Real estate activities
		11	Chemical and non-metal	25	Business services
		12	Iron and steel	26	Public administration
		13	Other manufacturing	27	Education
			Electricity	28	Health and social work
		14	Hydroelectricity	29	Other services
		15	Thermal		
		16	Solar photovoltaic		
		17	Water supply and sewage		
		18	Construction		

Source: Nkrumah (2024)

Elasticities and Other External Data

Information on elasticities is required to capture the behaviour of economic agents in relation to changes in relative prices, incomes and substitution between factors of production in the CGE model. First of all, due to the general lack of information on elasticity of trade and factor substitutions in developing countries, this study assumes an elastic factor substitution for most production activities (that is, $\sigma > 1$) while drawing on global trade elasticities (θ and φ) by Dimaranan as cited in Robinson and Lofgren (2005).

The IFPRI static CGE model is adapted for this exercise and calibrated with the 2015 Social Accounting Matrix (SAM). Production, trade, and consumption elasticities are adopted from GTAP 8 database (Aguiar et al., 2016), and from comparable developing countries like Kenya and Bangladesh. The SAM data is aggregated to 11 products and sectors with a split of the electricity sector into hydro, thermal and solar electricity. Also, agriculture products are aggregated into food, export, and other agricultural commodities.

Policy Experiments

Emissions tax and carbon capping

The experiments considered in this empirical chapter are teased out of key strategies outlined in Ghana's NDCs for the power sector that deal specifically with direct cuts in carbon emissions.

i. **BAU Scenario**: This describes the status-quo at mitigating carbon emissions in the power sector. According to the implementation plan of Ghana's NDC, the country's business-as-usual (BAU) emissions are expected to increase from 43.02 MtCO2e in 2016 to 48 MtCO2e in 2020, 59.1 MtCO2e in 2025 and 73.3 MtCO2e in 2030.

ii. **Tortoise Scenario**: This measures a slow-paced scenario where the country anticipates to reduce emissions based on its domestic capacity without external investments or support. In this scenario, Ghana aims to *unconditionally* lower its GHG emissions by 15 percent relative to its BAU levels by 2030. This translates into 62.3 MtCO2e in 2030

iii. **Horse Scenario**: Reduction in emissions in the country is expected to speed up to catch up with the pace of its peers with inflow of external support and investments. In this scenario, the country is targeting to *conditionally* reduce its carbon footprint by 45 percent relative to its BAU level in 2030. This will result in 40.3 MtCO2e in 2030

iv. **Cheetah Scenario**: This describes a more rapid cut in emissions up to 95 percent below the BAU level in 2030. The total carbon footprint drops drastically to 3.7 MtCO2e in 2030, almost a carbon-free economy.

Data Source and Type

Ghana's household expenditure surveys (the living standard surveys) for 2013 and 2017 are used measure residential demand for electricity. The Ghana Living Standard Surveys (GLSS) contain information on living conditions, household and individual information on demographic characteristics and other important information including education, health, employment, housing conditions, access to financial services and asset ownership.

This is intended to make available relevant data for policy and decision-makers to measure socio-economic indicators and appreciate their determinants so that data-driven programmes could be developed to address challenges in the various sectors of the economy such as health, education, economic activities and housing conditions, among others. Also included in the surveys are price indices and expenditure on goods and services consumed by households over the survey period. A total sample of 16,730 and 14,009 households with an average size of 4.3 and 4.2 people for 2013 and 2017, respectively, were used in the final analysis.

Other data sources such as household population estimates, national gross domestic product (GDP), and inflation (CPI) were used to uprate the monetary values in the GLSS 6 and 7 for years other than the survey year. These uprating statistics were also obtained from the Ghana Statistical Service annual GDP, CPI and population statistics. In Ghana, the exchange rate directly affects electricity prices as it appears as a key factor in tariff reviews. The is as a result of costs and investments in the electricity upstream being dollar denominated. Hence, the cedi's end-of-year exchange rate with the US dollar is obtained from the central bank to uprate electricity prices between years.

Model Variables

Key variables used to fit the household demand for electricity include prices and expenditure on electricity, annual household expenditure per capita and household size. The price of electricity is assumed to have a non-linear tariff structure, that is the increasing block tariff (IBT). The IBT differentiates consumers according to predefined consumption bands (blocks) and charges consumers within the same band an equal tariff but charges an elevated tariff as consumption band increases. This is consistent with regulated electricity pricing in Ghana, Africa and most parts of the world. For instance, as used in the empirical analysis, consumers of electricity in Ghana are divided into four groups based on the monthly unit consumption, namely: less than or equal to 50KWh, 51-300KWh, 301-600KWh, and more than 600KWh. These monthly consumption ranges attract different tariffs whereas consumers within the same band face equal tariff. Consumers consuming a maximum of 50KWh per month are considered as lifeline consumers and are mostly targets of government subsidies and other cash transfers.

Also, the welfare quintile variable is included as a key household demography for the purpose of disaggregating the impacts of policy reforms in RFITs on households. The spotlight is then thrown on households in first and last 20 percent, as well as households whose incomes or expenditure are near the poverty line. That said, household expenditure per capita is thus uprated using the year-on-year GDP growth, whereas the absolute poverty lines are uprated using the year-on-year CPI. No elasticities are assumed between uprating and uprated factors in a similar fashion by Verme and Araar (2017). Thus, the observed changes in the uprating factors (GDP, CPI and exchange rates) are applied directly to the uprated factors. Household sizes are assumed constant between the survey periods. the Lastly, household weights based on probability of selection, and ex-post probability of non-response during the survey is applied to the system of demand functions, thus, to correct for biases in estimates.

In the projected years beyond 2021 to 2030, the analysis presents two possible scenarios, namely: business as usual (BAU) case and an accelerated economic growth (AEG) case. These two scenarios describe the likely growth paths through to 2030 and the attendant rise in electricity demand, inflation and exchange rate changes. Hence, this study compares two possible cases for Ghana's growth trajectory till the end of 2030. In both instances, a constant population growth rate of 2.3 percent per annum is used. This is consistent with the country's population projections going forward. A summary of values used for the BAU and AEG cases are presented in the next section.

Model for Renewable Energy Feed-in-Tariffs (REFITs)

The third objective of this study seeks to assess the effects of renewable energy feed-in-tariffs (REFITs) as a financing tool for solar penetration in domestic electricity supply on revenue generation and income distribution. REFIT is the most popular financing tool for increasing on-grid renewable electricity globally. A microsimulation analysis is conducted on REFITs in developing countries to estimate the level of tax revenue to subsidize renewable energy generation as done under REFITs. A REFIT is a typical tax (negative subsidy) on electricity demand prices to subsidize production of electricity from renewable sources. Thus, to implement REFITs governments introduce renewable electricity price mark-up over composite conventional electricity charge to incentive the deployment of utility-scale renewable electricity. This has distributional effects on government revenues and consumption welfare.

The subsidy simulation – SUBSIM – tool by the World is a rapid simulation model designed to provide on-the-go distributional impacts of subsidies and ex-ante subsidies reforms on household poverty and inequality, and the government budget (Verme, 2017). The analytical tool is mostly applied to study subsidy reforms in developing countries seeking to free-up government fiscal space through subsidy removal on products deemed mature for the free market.

The simulation analysis carried out in this study is underpinned by the World Bank's subsidy simulation tool, SUBSIM, which is widely adopted for ex-ante subsidy reforms in many developing countries (Araar et al., 2017; Verme & Araar, 2017). According to Verme and Araar (2017), SUBSIM model estimates the direct and indirect impact of subsidies reforms on household welfare, poverty, and inequality, and on the government budget with or without compensatory cash transfers. It can be applied to energy and food subsidies and accommodates linear and nonlinear pricing (ibid). The analysis herein demonstrates the technique for accounting for REFITs in the final electricity price as a reform that directly induces changes in government revenue and consumer welfare using the SUBSIM model.

In the model specification, the final consumer price of electricity charged by Ghana's sole electricity retailer is considered to consist of an energy charge set by the market regulator plus a monthly service charge, levies which include streetlight and national electrification levies, and subsidies. That is,

$$p_b = energycharge + servicecharge + sll + nel - subsidies,$$

where sll and nel are streetlights and national electrification levies, respectively. The subscript b represents consumption blocks.

It is worthy to point out that REFITs are government subsidies to producers of renewable electricity funded through raising of electricity prices. Put differently, the government raises prices of electricity in the form of 'renewable electricity premium' and uses the revenue to fund subsidies in the form of REFITs to producers. Thus, other than a subsidy reform analysis using the SUBSIM, REFITs enter the model as a price premium, otherwise a negative subsidy, paid by consumers. By so doing, the study implements a direct impact analysis of a (negative) subsidy reform from 2013 when Ghana set its first REFITs to 2030 when the country is targeting a 10 percent renewable electricity penetration.

Solar REFIT set in 2013 was more than twice (114%) of the average electricity tariff for conventional electricity. This REFIT is set for a guaranteed period of 10 years subject to a review every two years (Meyer-Renschhausen, 2013). For lack of information on the reviewed prices, the author set a 5 percent fall in the REFITs premium over conventional electricity charge on a reducing-balance scale from 2013 to 2021. This was done to account for price adjustments in conventional electricity due to rising operational and maintenance costs in the years after 2013.

The national renewable electricity penetration target is achieved cumulatively over a period. Thus, for a 10 percent penetration over 10-year REFIT regime, it is assumed, in this study, to have attained a percentage penetration every year for 10 years. Hence, for every year a cumulative percentage of the REFIT premium is passed is passed unto the consumer price as a negative subsidy (or tax). For example, in 2013, 1 percent renewable electricity penetration is achieved, hence the final electricity price for 2013 included a 1 percent added REFIT premium, in 2014 a 2 percent REFIT premium, and so forth up to 2023 a 10 percent REFIT premium added to the final electricity price.

Model specification

The microsimulation analysis herein is delimited to household demand for electricity which represents the biggest fraction of the total grid electricity demand in developing countries. In Ghana, residential demand for electricity represents 47 percent of total electricity demand (Ghana Energy Commission, 2022). In this regard, the incidence of REFITs will largely fall on residential consumers in developing countries.

Consumer welfare

First, the study assumes Cobb-Douglas expenditure function to measure consumer utility. This utility function is widely used in literature to accurately measure commodity substitution and account for large price changes. The latter feature is missed when using the linear expenditure approach mostly used in studies to capture small price changes, and, thus, over or underestimates welfare impacts. The author of this study strongly believes that the resultant price changes due to REFITs could be large and very significant and, hence, the choice of CD function over linear marginal approach. Initial total monetary expenditure before the reform will be:

$$C_1 = p_{e_1} q_{e_1}^{\alpha} \times p_{o_1} q_{o_1}^{\beta}$$

Where C_1 is initial total consumer expenditure, p_{e_1} is initial price of electricity, q_{e_1} is initial quantity of electricity consumed, and p_{o_1} and q_{o_1} respectively represent composite price and quantities of all other household goods, while α and β refer to expenditure shares for electricity and other goods, respectively. Following the introduction of REFITs, we have:

$$C_2 = p_{e_2} q_{e_2}^{\alpha} \times p_{o_2} q_{o_2}^{\beta}$$

By normalising prices at equilibrium, authors like Verme (2017) argue that the last units of the two goods, electricity and composite of other goods, will yield the same level of utility. Thus, regardless of any behavioural response by consumers including changes in quantities of electricity consumed in relation to other goods will practically yield the welfare. By this assumption, changes in welfare (w) can be simply assessed through changes in any of the two consumer goods in the form: $\Delta w = \Delta q_e = -\alpha q_e^{\alpha-1} \times dp_e$

Normalised prices further lead to

$$\Delta w = -\alpha C_e^{\alpha-1} \times dp_e \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (26)$$

Where dp is relative price change and Ce is electricity expenditure after the reform. However, since electricity price is commonly multi-level pricing (that is, increasing block tariff (IBT) and volume differentiated tariffs (VDT)), Equation (26) can be rewritten in the case of IBT as:

$$\Delta \mathrm{w} = -Ce_{h,b}\left(\frac{1}{\prod_{b=1}^{\mathrm{B}} \varphi_{e,b,z|qh}{}^{\alpha_{e,h}}} - 1\right)$$

Where $\varphi_{e,b,z|qh}$ refers to the average weighted post reform price of electricity consumed within block b, and is based on block z, which depends on the total consumed quantity (q_h); $\alpha_{e,h}$ is the expenditure share of electricity in household, h.

Government revenue

REFITs are, first, a consumption tax on consumers. Thus, the change in tax revenue (r) for the government is a function of consumer response to price changes after the reform as follows:

$$\Delta r = \sum_h C_{e,h} dp_e \left(1 + \epsilon_k(\tau_k + dp_k)\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (27)$$

Where τ_k is the unit tax (REFIT) for product k (herein, electricity). The unit tax, $\tau_k = -s_k$, where s_k is the unit subsidy on product k in the original SUBSIM model. Also, C_h is total consumer expenditure, dp_k is change in price because of the REFIT, and ϵ_k is elasticity of demand.

It is important to state that in the simulation a constraint is placed on Equation (34) to restrict the maximum decrease in quantity to that the initial quantity in case of very large price changes. This is to prevent possible negative quantities of demanded due to large price hikes.

Data sources

At the core of the simulation is the sixth round of Ghana Living Standard Survey collected in 2016/17 the year in which Ghana introduced its first 3MW of solar energy unto the national grid by the national power producer, Volta River Authority (VRA). However, annual GDP per capita growth, consumer price index (CPI) and population estimates from World Development Indicator (WDI) to recursively update household consumption expenditure per capita and poverty lines for ten years 2016-2030, a typical lifespan of REFIT in Ghana. Other data used include electricity prices by the Electricity Company of Ghana (ECG) (2016 tariff reckoner) and 2016 REFITs from Ghana's Public Utility Regulatory Commission (PURC).

Elasticity of demand for electricity

The SUBSIM model is calibrated using residential electricity demand elasticities. There are practical difficulties associated with correctly specifying price elasticity especially for the regulated electricity market where prices are uniform across the country. First is lack of variation in prices in surveys which makes it impossible to compute the demand elasticities when prices change. Secondly, known price elasticities in literature for residential electricity pegged around 0.5 are mostly for advanced countries whose economic fundamentals are different from the global south. So, the analysis first simulates possible cases from 0.1 – 0.5 for 2016 and compare results to select the most suitable elasticity in relation to known poverty and inequality estimates for 2016.

Chapter Summary

The foregoing chapter discussed proposed research methods that guides the conceptualisation and implementation of study, as well as the analyses necessary to achieve the stated research objectives. The chapter began by stating the research paradigms, designs, and methodologies that underpin the study. Specifically, the author associates this study with the post-positivist philosophy and quantitative paradigm that permit an objective test of hypotheses including those professed under this study.

The analysis therefore follows a quantitative modelling approach using the so-called computable general equilibrium models, and a microsimulation model to measure the rapidity and impacts of energy transition strategies in Ghana's electricity sector, namely: carbon emissions taxation, deregulation of the wholesale electricity market, and incentivisation of renewable grid electricity penetration through feed-in-tariffs. The CGE modelling is calibrated with the Ghana's Social Accounting Matrix (SAM) as well as a diverse data source for production, trade and demand elasticities, whereas data for microsimulation of FITs is obtainable from Ghana's Living Standard Survey (GLSS 7) and electricity prices from Ghana's Public Utility Regulatory Commission (PURC) and the electricity retail company: the Electricity Company of Ghana (ECG). The rapidity of transition implemented in the CGE models, and the FIT microsimulations are based on Ghana's updated NDCs from 2020 to 2030.

CHAPTER FOUR

RESULTS AND DISCUSSION

This chapter, the results from CGE modelling of carbon taxation and carbon capping policy scenarios, and renewable electricity feed-in-tariffs (REFITs) are presented and discussed. The results are organised into impacts of a carbon tax and carbon caps policies in thermal electricity generation in Ghana under three subheadings: (a) impacts on the electricity production; (b) impacts on the real national economy; and finally (c) impacts on consumer welfare. After that is a discussion on the impacts of REFITs on residential electricity demand, government revenue, and consumer welfare. Last but most importantly, the opportunity cost of no-action for REFITs by 2030 is discussed at the end. The result for each objective is preceded by the adopted estimation technique. Before all of these, however, the next paragraphs discuss briefly the baseline economy to which policy scenarios will be compared.

The Baseline Economy of Ghana

The structure of Ghana's economy post-independence has been one heavily reliant on export of commodities and the agriculture contributing the largest share of national GDP (Fosu & Aryeetey, 2008). However, according to Fosu and Aryeetey, this trend changed in the early 2000s with share of the services sector overtaking both agriculture and industry. Thus in Figure 7, Ghana's economy transformed from an agriculture-led to services-led by the end of 2010 (Jedwab & Osei, 2012).

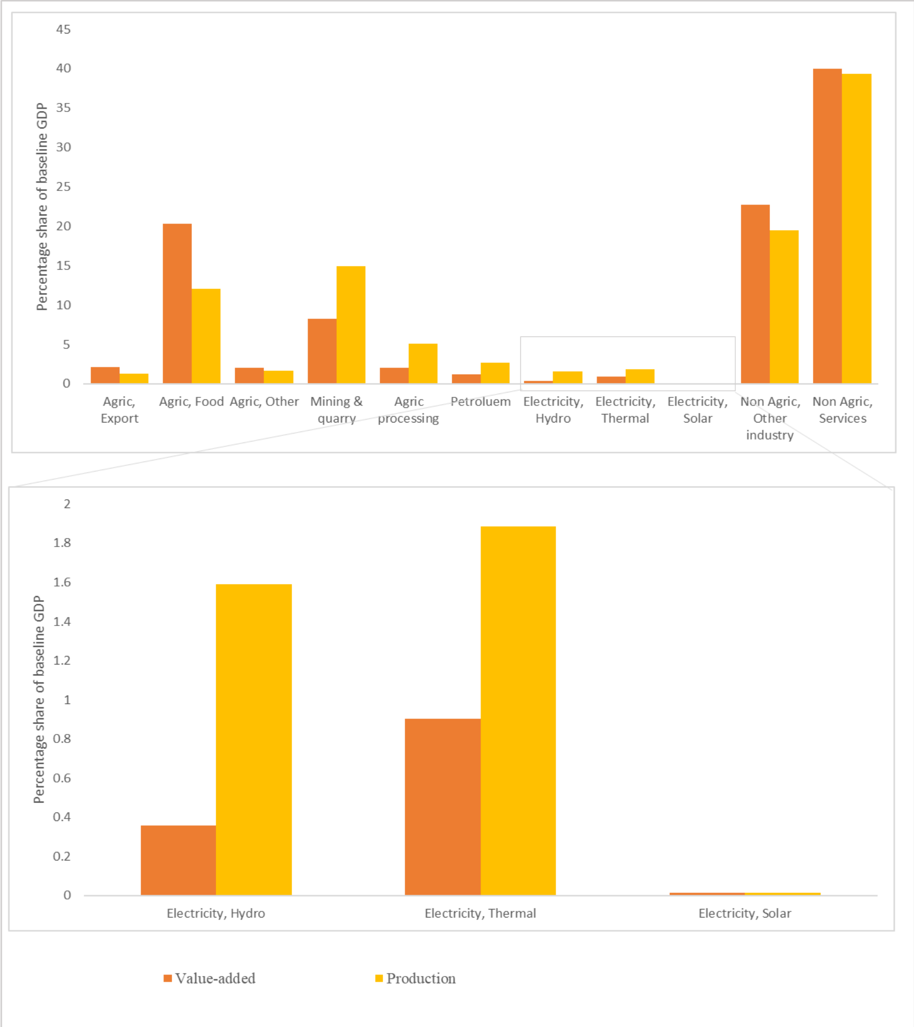

Figure 7: Value-added and gross output shares of baseline GDP
Source: Nkrumah (2024)

By 2015, the services sector contributed the largest share of value-added GDP or gross output out followed by industry, food production, and mining and quarry sectors, respectively. An extensive but aggregated sectorial employment, exports and import shares have been presented in Table A3 in the appendix of this document. It is also evident in Figure 8 that commodity exports and other agriculture sectors, as well as the energy sectors had lower contributions to value-added GDP and gross output.

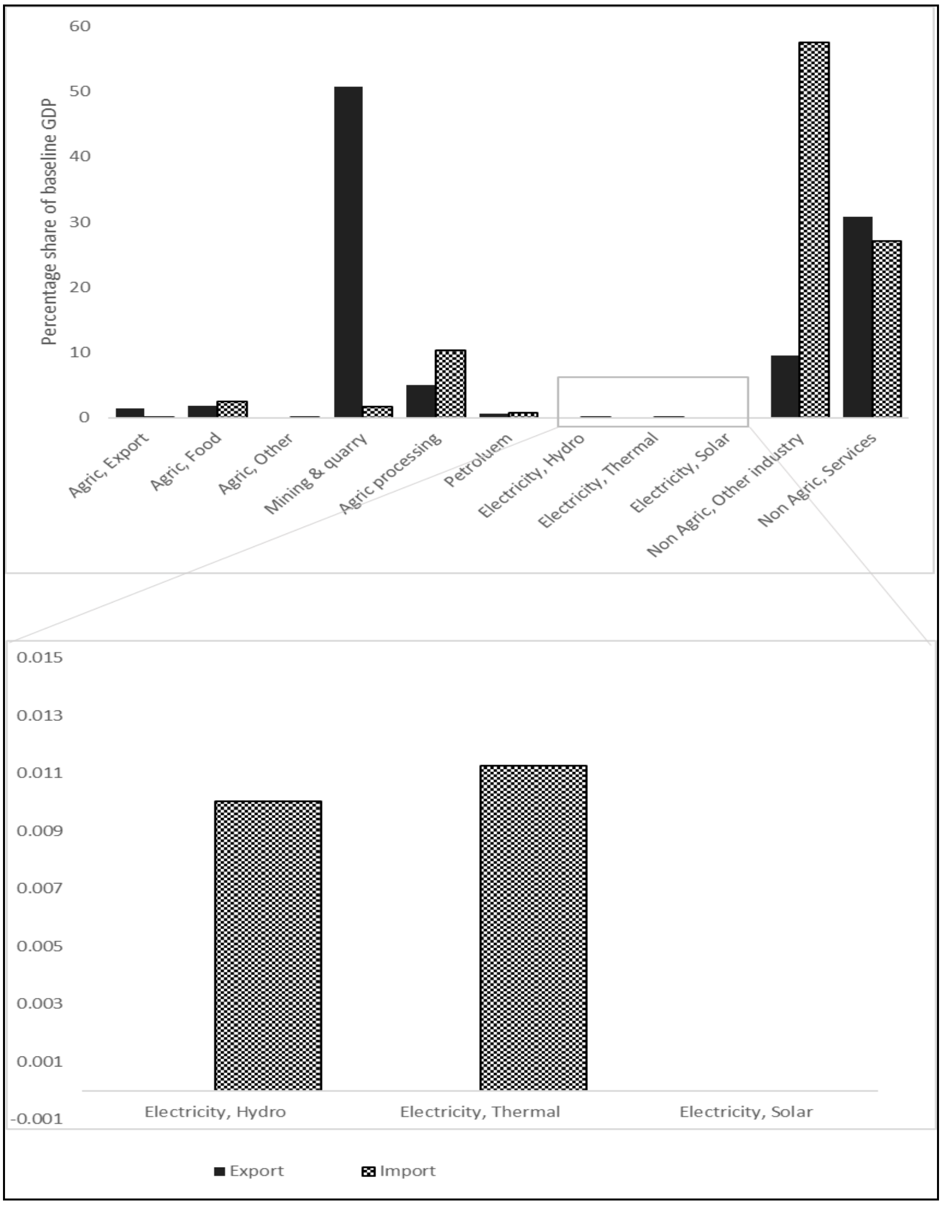

Figure 8: Export and import shares of baseline GDP
Source: Nkrumah (2024)

The electricity sector (zoomed out in the lower panel, Figure 8), in particular, shows less than a percentage share of value-added for both hydro and thermal electricity, respectively. Similarly, hydro and thermal electricity contribute less than 2 percent, specifically 1.6 and 1.85 percent, respectively, to gross national output. The least is solar electricity which contributes roughly 0.1 percent to both value-added GDP and gross output.

Added to the above, Ghana's economy in the 2015 baseline had a higher shares of commodity exports in the mining and quarry sectors, as well as the services sector (see Table A3 in appendix). The mining and quarry sectors were predominantly crude oil, gold and other minerals exports (Okyere & Jilu, 2020). Imports were highest for industrial products, and the services sector. Value of electricity imports in the peak of Ghana's power supply crises (locally known as "Dumsor") occupied very low shares of total imports, about 0.011 and 0.01 percent of total imports for thermal and hydroelectricity, respectively. These are shown in Figure 8.

Flipped around, Figure 9 presents the component shares of consumption GDP, and share of net taxes for the 2015 base year. It shows total absorption as a percentage of GDP stood at 111% comprising private consumption (67%), fixed investment (24%), stock changes (5%) and government expenditure (15%). Economic leakages through negative net exports adjusted domestic absorption shares upward. Finally, tax revenue as a share of GDP was 10 percent, a performance which is below like-countries in sub-Saharan Africa

Lastly, Figure 10 further presents the distribution of factor employment in the economic sectors in the base year, especially fuel inputs in electricity generation. It is interesting to note how Ghana's agriculture export sector like cocoa, shea, cotton, etc, employs unskilled labour to about half of its factor inputs, largely on small-holder agriculture land. Similarly, agriculture activities for food production also significantly rely on unskilled labour, small-holder capital and land – characteristic of lack of mechanized large-scale agriculture in Ghana for the base year.

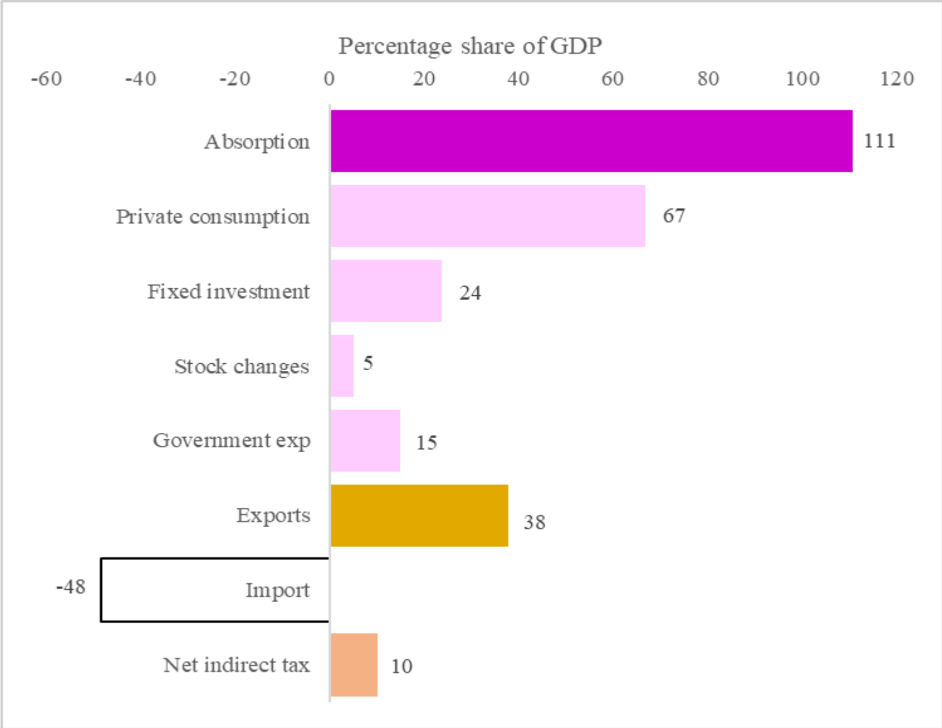

Figure 9: Shares of aggregate consumption in the baseline
Source: Nkrumah (2024)

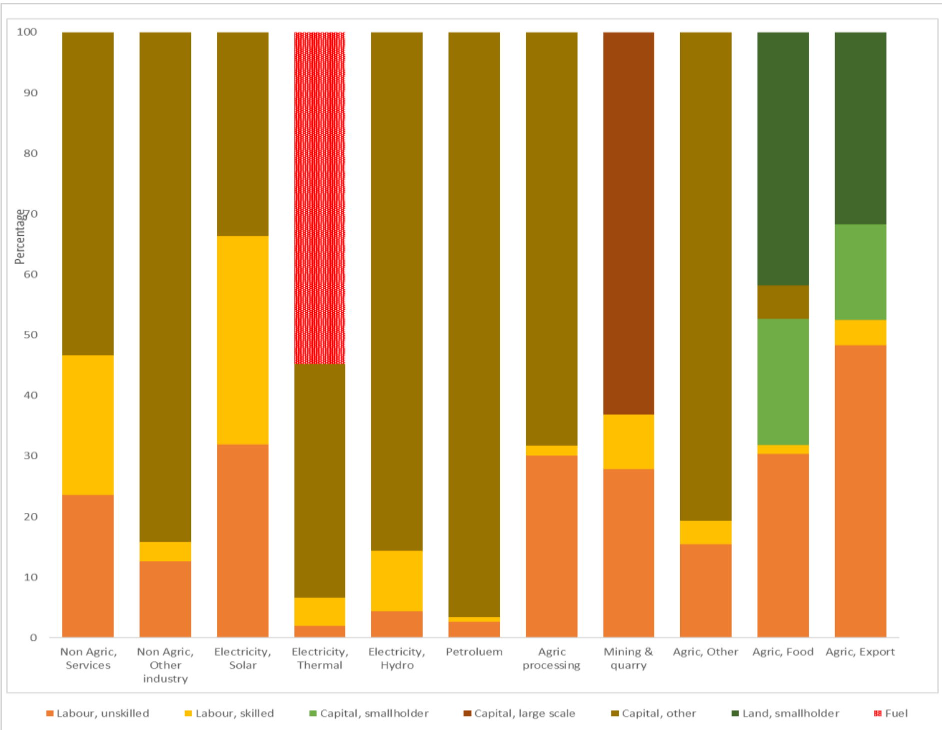

Figure 10: Input share within the national sectors
Source: Nkrumah (2024)

Mining and quarry, as well as hydroelectricity, on the other hand, employs a high share large-scale capital and about a third of its labour employments are for the unskilled, pointing to the influx unskilled labour in small-scale, artisanal mining and, sometimes, illegal mining ("Galamsey") (see, Figure 10). Talking about hydroelectricity and the electricity sector on a whole, the sector is capital intensive. Fossil fuel as factor input is modelled in the CGE to be used only in thermal generation occupied more than half of the base-year' factor costs. Unlike hydro and thermal electricity, share of labour cost is substantial in solar electricity generation.

Impacts of Carbon Taxation on Growth and Welfare

Now, the results of the policy experiments implemented in this study are discussed. The ex-ante analysis set out in this study as BAU, Tortoise, Horse, and Cheetah measure the rapidity of emissions abatement through carbon taxation in the electricity sector towards the global energy transition. The impact of each scenario is presented as percentage deviations from the baseline economy as briefly described above. The discussion in here is broken down into impacts on the electricity sector, impacts on government savings, impacts on general economic growth, and finally on consumer welfare. In the first place, however, the techniques for estimating carbon taxes are put forward.

Techniques for estimating carbon tax scenarios

First of all, carbon tax is modelled in this present study as a fiscal shock in a general equilibrium framework using IFPRI static CGE to analyse policy scenarios in relation to emissions abatement targets in Ghana's nationally determined contribution (GH-NDCs) towards the Paris Agreement on climate change. In the updated GH-NDCs in 2021, Ghana has committed in the next decade to 19 policy actions in 10 priority areas, mainly in the energy and the electricity specifically (MESTI, 2021). These policy actions translate into 13 adaptation and 34 mitigation programmes of action among which the electricity sector will witness a switch to 100 percent natural gas use as fuel for electricity generation, and 10 percent penetration of renewable electricity by 2030.

Out of the 34 mitigation measures, Ghana aims to implement 9 unconditional and 25 conditional programmes of action that would cumulatively cut 24.6 MtCO2e and 39.4 MtCO2e by 2030, respectively, compared to the 2020-2030 cumulative emissions in a baseline scenario (MESTI, 2021). Based on the above, the study conducts four policy experiments on carbon taxation in the business as usual (BAU), unconditional, conditional, and rapid cases. These scenarios are christened the Tortoise, Horse and Cheetah scenarios, respectively.

According to Haites (2018), optimal tax rate can be set the rate equal to the estimated benefit of reducing GHG emissions by 1 tonne CO2, the so-called social cost of carbon (Partnership for Market Readiness, 2017), or better still set the rate at which the country is willing to pay for equivalent units from renewable sources. For the purpose of this study, the equivalent rate for the carbon tax is the feed-in-tariff applied in 2013, which 40.21 pesewas per KWh of solar PV. In the model simulation, nonetheless, the tax rate is computed for unconditional, conditional and rapid scenarios contained in Ghana's updated NDCs by multiplying the deviation of abatement from the BAU case over the emissions from electricity generation as well as the feed-in rate to obtain the carbon charge per volume of pollution from thermal electricity. That is, $E_s = \frac{\delta\tau}{g}$

Where g is grid emissions from electricity[1] and τ is feed-in-tariff for solar PV, and δ is the percentage deviation of emissions from the BAU by the scenario in question. Finally, E_s is the scenario in question. Table ***6*** presents the values for variables used in the carbon tax scenarios.

Table 6: Carbon tax scenarios

Experiment	Deviation from BAU levels	Emissions from electricity generation (MtCO2e)[2]	Feed-in-tariff for solar PV generation (GHS/KWh)	Applicable carbon tax rate (GHS/MtCO2e)	Applicable carbon tax rate (US$/MtCO2e)[3]
BAU	0%	4.8557	0.4021	0	0
Tortoise	15%	4.8557	0.4021	0.0124	0.006
Horse	45%	4.8557	0.4021	0.0373	0.019
Cheetah	95%	4.8557	0.4021	0.0787	0.039

Source: Nkrumah (2024)

According to MESTI (2021), Ghana's 'Tortoise' case will reduce emissions by 15 percent below BAU levels by 2030, whereas the ' Horse' scenario will achieve additional 30 percent below BAU level. Hence, a cumulative 45 percent fall in emissions from BAU to the conditional case. Finally, a more rapid scenario not contained in the GH-NDC, 'Cheetah' scenario, to gauge the impacts of an extensive tax rate that achieves 95 percent

[1] See EPA (2019, p. 130) on emission from electricity generation computed at 93.2% of total 5.21MtCO2e from energy industries.
[2] See EPA (2019, p. 130) on emission from electricity generation computed at 93.2% of total emissions from energy industries
[3] Cedi-US dollar exchange rate in 2013 was 1.9968 (Public Utilities Regulatory Commission (PURC), 2013)

of emissions below BAU level are introduced. A full (100%) recovery of carbon tax will yield GHS 0.0828 per metric ton of CO_2.

Carbon tax and the electricity sector

The impacts of carbon tax on the electricity sector are presented and discussed under two subheadings. The first focus on the impact on electricity supply with the second focussing on the impact on electricity price.

Carbon tax and electricity supply

Direct impact of carbon tax on the electricity sector falls on generation entities to internalise the cost of air pollution from the upstream, as noted by Dasgupta (2021) and, Stern and Stiglitz (2021). These authors have argued that carbon taxes as a Pigouvian fee seeks to correct a market failure caused by environmental externality in production and consumption activities. A recent empirical finding by (Zhao et al., 2023) for Northern Europe, in a similar form, identified spillovers between the carbon and the electricity markets through price fluctuations due to carbon pricing mechanisms. Also, in Japan Yoshino et al. (2019) found that revenue from carbon if used to fund renewable energy projects accelerates private investment into green projects. Hence, the results of this current analysis shows that the impact of a carbon tax in the thermal electricity generation, generally, would have a spillover effect on hydroelectricity and on solar generation through multiple price-rebound-effects in domestic goods and services (Figure 11).

Thus, domestic electricity supply compared to the baseline year increases by almost 4 percent in the Tortoise scenario with a carbon tax rate of GHS 0.0124/$MtCO_2e$ of gross output, while the reverse is true for a higher tax rate of GHS 0.0787/$MtCO_2e$ in the Cheetah scenario (Figure 11).

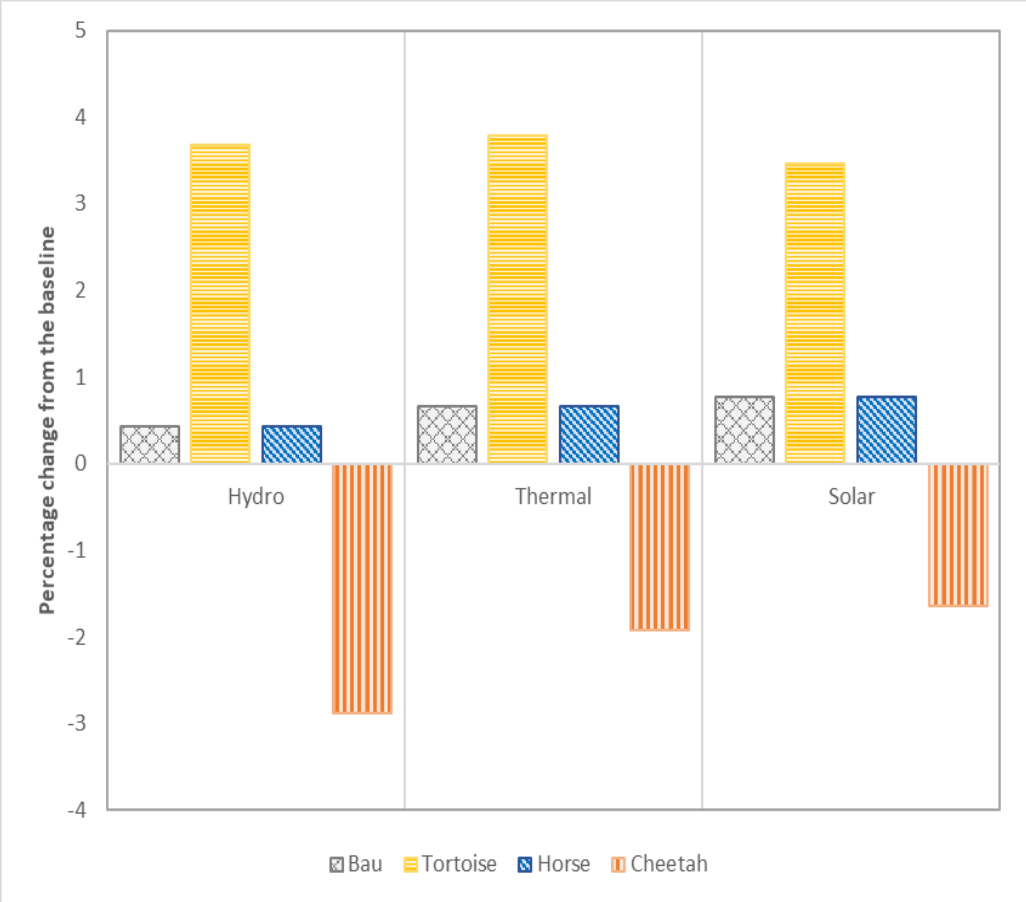

Figure 11: Impact of carbon tax on electricity output
Source: Nkrumah (2024)

The Business-as-usual case where no carbon tax is applied provides a path to understanding what is happening in the electricity sector when such tax is introduced. As could be seen, the BAU case presents a gradual shift in generation from hydro to thermal and solar electricity, even before an introduction of a carbon tax in thermal generation. Hence a stronger effect on hydroelectricity supply even in the highest carbon tax (Cheetah scenario).

A moderate tax rate (GHS 0.0373/MtCO2e in the Horse scenario) to a minimal tax rate (GHS 0.0124/MtCO2e in the Tortoise scenario) still generates higher outputs over the base year. For instance, a 4.5 percent tax rate will yield 3.67, 3.79, and 3.46 percent of hydro, thermal and solar electricity, respectively, compared to the base-year. The reverse is, however, true that a lofty carbon tax (29.5%) on thermal generation will decrease domestic production below base-year levels.

Carbon tax and price of electricity

On the other hand, final demand price of electricity drops significantly for hydroelectricity in all scenarios, particularly the Cheetah policy scenario. Although in Ghana's case, the regulator, the Public Utility Regulatory Commission (PURC) determines the retail price of electricity, the merit-order of generation sources used by the national power aggregator takes into account the marginal price of each technology source to arrive at a composite charge for electricity in the retail market. Thus, the average price of electricity becomes the weighted average price of electricity produced using hydro, thermal and solar technologies. Therefore, the study shows that except in the Tortoise scenario for thermal and solar, prices of electricity by source decline significantly, especially for high tax rates compared to the base-year (Figure 12).

The falling prices could be as a result of excess supply over the base-year inducing shifts to electricity alternatives. The latter would be an extreme and less likely case since electricity has no perfect substitutes. Thus, what seems more plausible is the former argument of excess supply as shown previously in Figure 11. This is corroborated by Mills et al. (2019) who analysed the historical wholesale power crises between 2008 and 2017 in the United States and concluded that excess supply of electricity resulted in negative and falling prices.

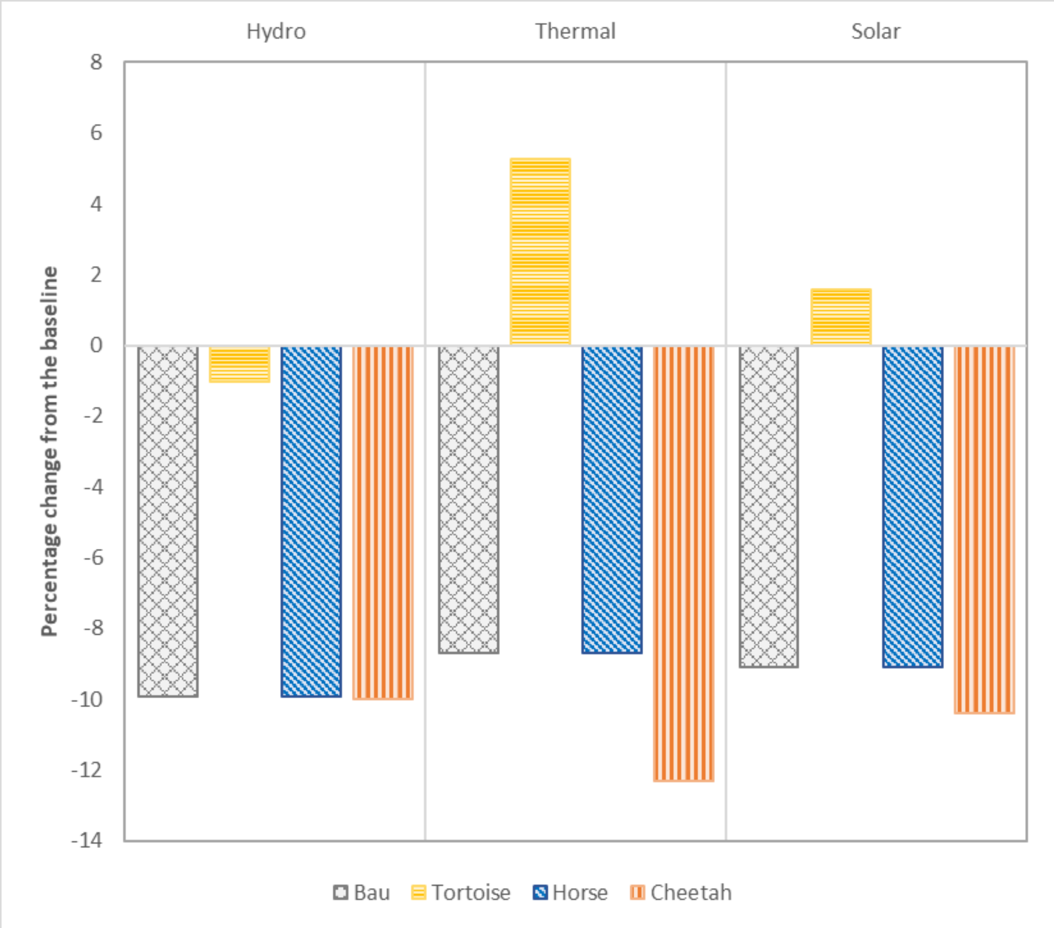

Figure 12: Impact of carbon tax on price of electricity
Source: Nkrumah (2024)

In this regard, the sharp decline in prices is as a result of price inelasticity of electricity demand and, thus, such a rise in supply induces larger declines in price. As already stated, prices of thermal and solar electricity exceptionally increased in the Tortoise scenario. It is a known fact that a new production tax increases industry marginal cost, and as the result industry price also increases. This directly increases industry supply coupled with the shift in hydroelectricity to thermal and solar as identified in Figure 11.

Carbon tax and government's fiscal balance

Carbon tax is unique among emissions abatement tools at the disposal of governments around the world in the sense that it provides revenue to governments that could be invested into critical infrastructure and technologies to accelerate transition to clean energy (Bergh & Botzen, 2020; Fremstad & Paul, 2019). Carbon tax revenues are also used to subsidize production and consumption of renewable energy as well as direct cash transfers to poor households to mitigate the adverse distributional effects of such taxes that are easily passed on to the final consumer (Tvinnereim & Mehling, 2018).

The model closure adopted in this analysis hold both taxes and government revenue as exogenous while the fiscal balance (i.e., government savings) endogenously adjusts to establish equality between revenue and expenditure. This closure, therefore, does not allow the government to endogenously adjust direct tax rates nor alter its expenditure lifestyle, and hence permits an assessment of a policy shock on the government's final savings or dissavings. In Figure 13, government savings are negative (except in the Cheetah Scenario), highly driven by government expenditure. Generally, when government expenditure increases, its savings goes negative, and vice versa. The Tortoise scenario presents the worst fiscal balance on government's books, and even though revenue from carbon taxes increases astronomically, hike in government expenditure overturns the gains in revenue.

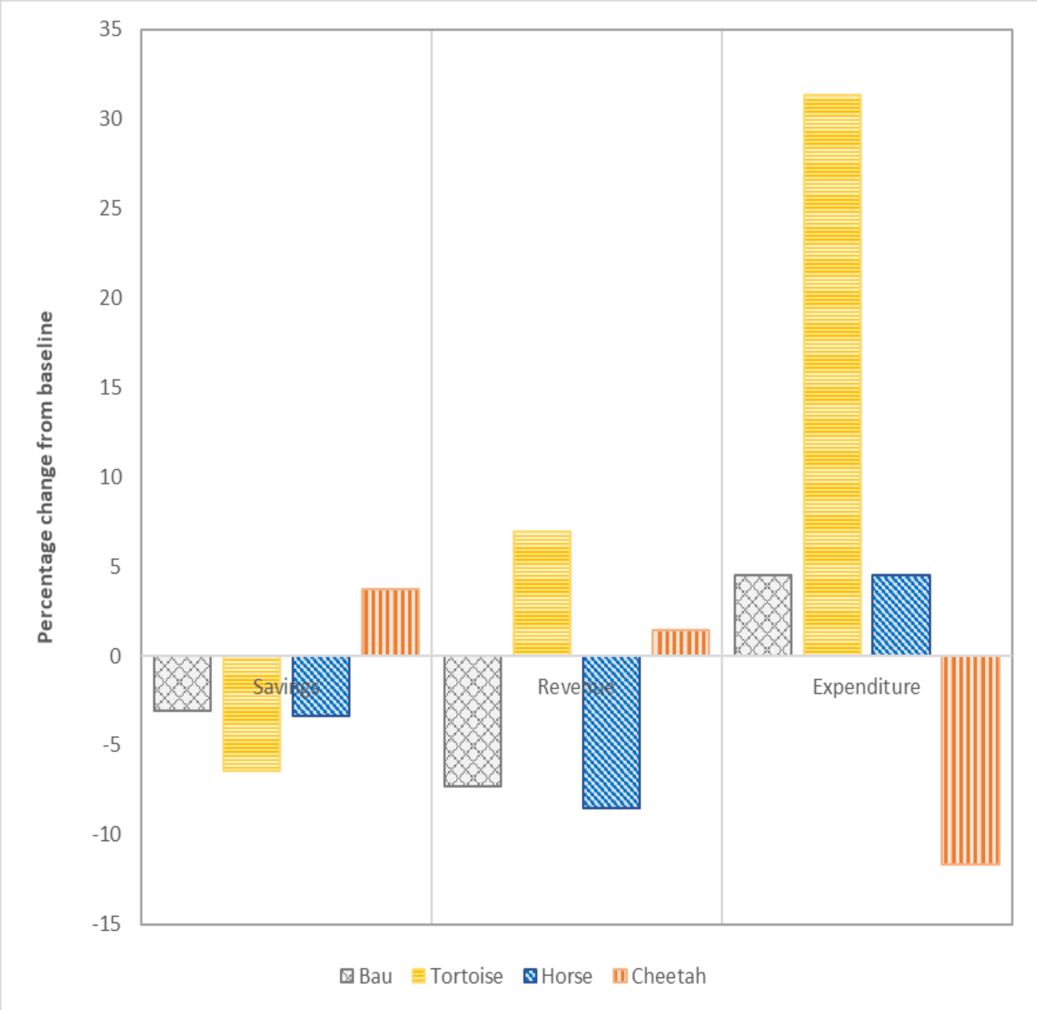

Figure 13: Impact of carbon tax on government's balance
Source: Nkrumah (2024)

Carbon tax and economic growth

The electricity sector plays important role in national prosperity and economic growth. Hence, an introduction of a carbon tax on thermal electricity production will have ripple and feedback effects within and across national sectors, and ultimately impact economic growth. Figure 14 shows the impacts on aggregate demand over the base year, 2015, disaggregated into component shares. In the BAU case, share of absorption declines by approximately 4 percent, likewise private consumption, investment, stock changes and international trade.

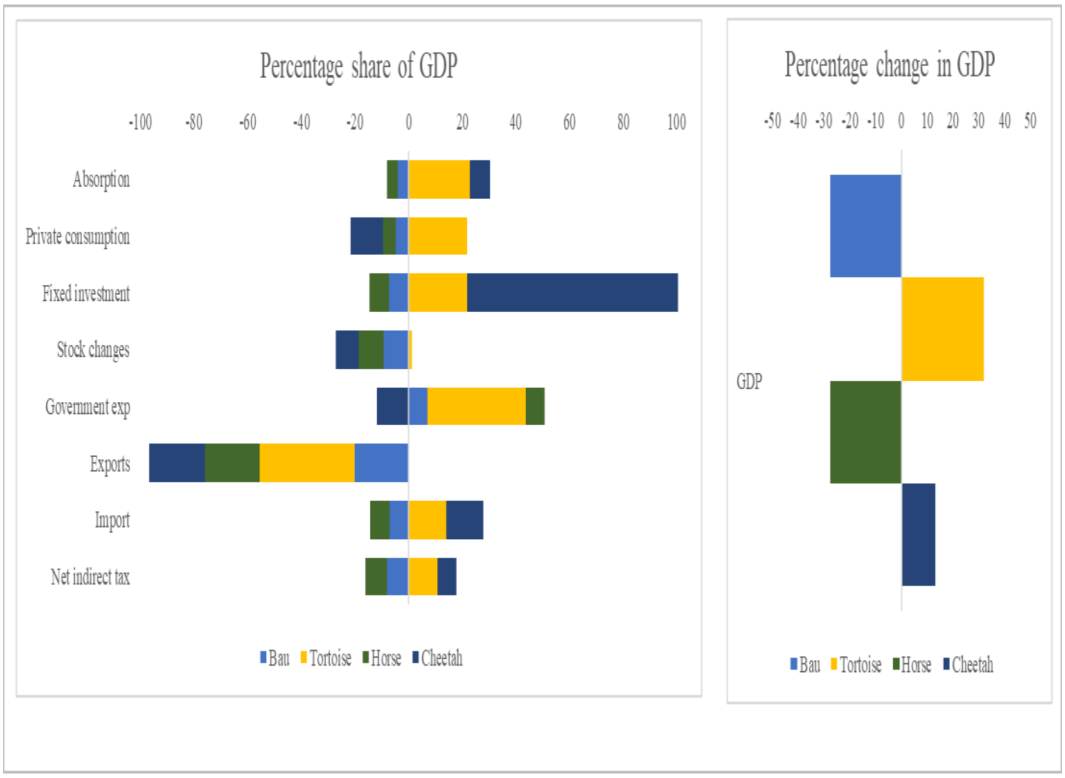

Figure 14: Impact of carbon tax on economic growth
Source: Nkrumah (2024)

Only government expenditure increases in the BAU case. On the other side, the Tortoise scenario increases the share of absorption significantly by about 23 percent, largely influenced by increases in government expenditure, perhaps financed through carbon tax revenues (Arndt et al., 2016), fixed investments, and private consumption.

Import also increases in the Tortoise scenario. Thus, a minimal carbon tax rate still induces about 32 percent growth compared to the baseline. Notwithstanding, exports decline in the Tortoise scenario and for all other scenarios. Conversely, the Horse scenario has adverse impact on overall GDP manifested in absorption, except government expenditure. Exports and imports are also lower than base year growth shares. The Cheetah scenario have rather mixed impacts on the different components of aggregate demand; it has an impact on overall GDP through absorption, particularly fixed investments.

Finally, share of indirect tax in overall GDP increases in the Tortoise and Cheetah scenarios whereas the shares fall in BAU and Horse scenarios. Overall, the impact of carbon tax on growth is generally negative, except in the case of the Tortoise. This is supported by the plethora of empirical studies like (Coffman et al., 2023; Dissanayake et al., 2020; Xie et al., 2020) that examined the negative impacts of carbon taxation on economic performance. These studies, however, acknowledged that by adequate revenue recycling, a positive impact on economic will not be unlikely (Saelim, 2019).

Also, Figure 15 presents the distribution of growth among national sectors, contrasting nominal with real GDP growth over the base-year. It could be observed that, GDP shares of individual sectors in the BAU scenario decrease below their baseline levels in both real and nominal growth. Unsurprisingly, spikes in nominal GDP are generally higher than real growth due to domestic inflation.

Agriculture exports share of GDP fall below the base-year in both nominal and real sense; the most consistent scenario in both nominal and real growth is the Tortoise case where the decline is roughly 11 percent in both growth measurements. This is similar to what Dumortier and Elobeid (2021) also found in the United States that carbon taxes on energy inputs reduces land allocated to crops, thereby reducing agriculture output growth.

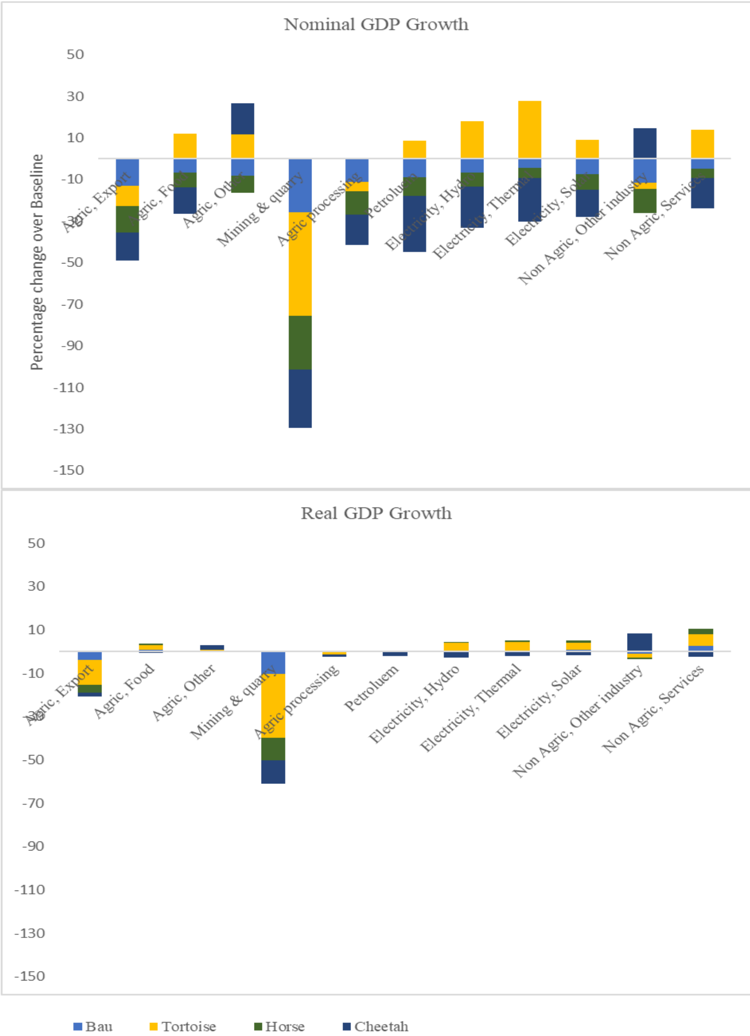

Figure 15: Impact of carbon tax on real sector growth
Source: Nkrumah (2024)

Further, food and other agriculture sectors are largely influenced by inflationary prices such that at constant prices, the contribution of the sectors shrinks close to that of the base-year. This is also true for the remaining sectors, except mining and quarry sector whose shares of GDP, in both nominal and real terms and across all scenarios, declined below the base-year's shares. The electricity sectors in particular recorded higher nominal growth compared to the baseline in only the Tortoise case but in real terms, there were marginal increases over the baseline in the BAU, Tortoise, and

Horse scenarios. The highest carbon tax rate scenario yields a negative real growth compared with the baseline as also argued in the preceding paragraph.

Carbon tax and consumer welfare

Finally, the implications of rapidity of the carbon tax in thermal electricity on consumer welfare losses (equivalent variation) are discussed. Equivalent variation is an ex-ante measure of the change in income of the consumer required to make him/her indifferent about a change in price as a result a policy shock (Araar & Verme, 2019; Verme, 2017). In other words, it measures how much a consumer would like to receive or pay to be on the new equilibrium after a price change. The change in income to be received or foregone by the consumer, respectively in that regard, indicates the welfare loss or gain accompanying the policy in question.

The incidence of welfare changes in Figure 16 is evidence that the non-poor households in urban areas have highest incidence of welfare loss, especially in the BAU scenario. This rather surprise finding for the BAU case could be attributed to the declined contribution to government revenue and GDP growth as discussed in the previous sections. The urban households are mostly the largest beneficiaries of economic growth, hence a fall in growth would mostly burden consumers in the urban centres, and in this case, the non-poor urban households. The poor in both rural and urban areas have lower incidence of welfare burden requiring income transfer (subsidies) from government to cope with the price changes in the BAU scenario.

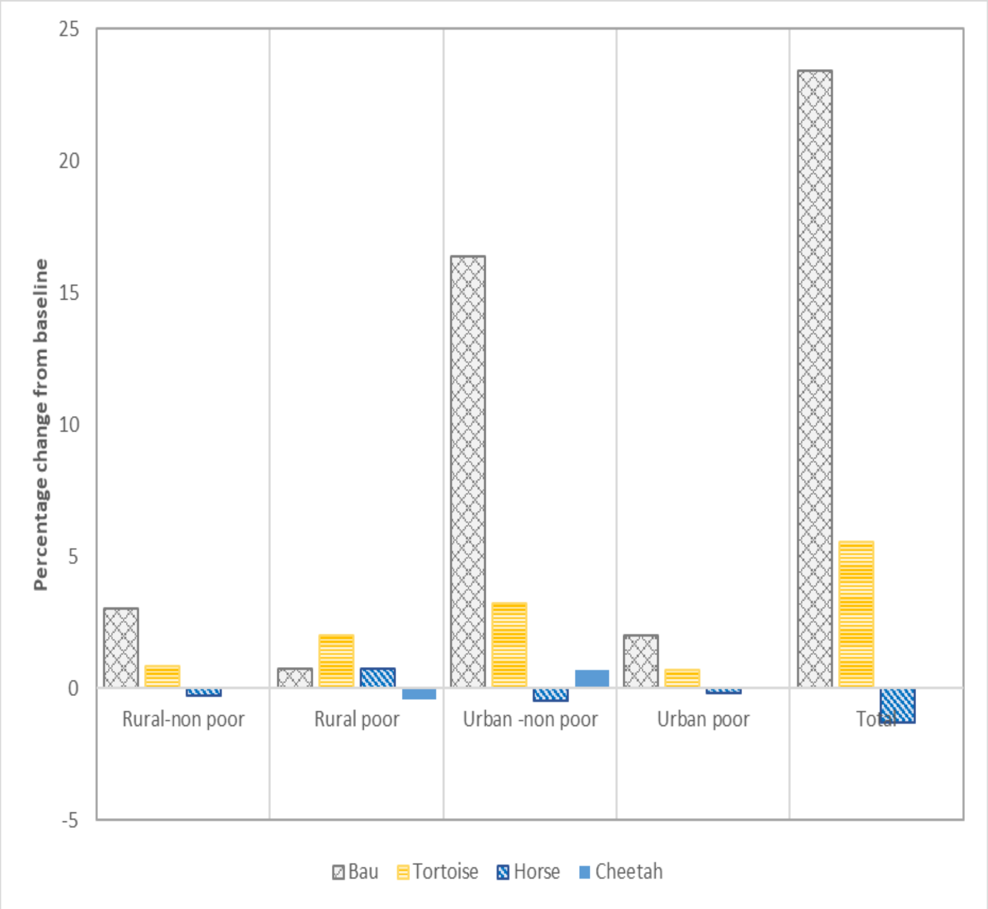

Figure 16: Impact of carbon tax on consumer welfare
Source: Nkrumah (2024)

Generally speaking, Figure 16 depicts that rapid tax rates have rather lower welfare burdens on consumers possibly through linkages effects from increased government expenditure (Reaños & Lynch, 2022) (see also, Figure 13 & Figure 14). It could be explained as taxes raised are compensated through increased government expenditure to support private consumption and investment given the base-year's expenditure shares of the government and no endogenous change of its spending lifestyle. Per the argument of Saelim (2019), when carbon tax revenues are recycled through socially include programmes for vulnerable groups, it could reduce the poverty rate and improve the welfare of poorer households. As a result of this, welfare burden drops between the BAU case of no carbon tax to a minimum tax in the

Tortoise scenario. Once again, the urban non-poor have the highest welfare burden followed by the rural poor.

In conclusion, this study set out to assess the impacts of carbon taxes on economic growth and the electricity market using scenarios built on Ghana's commitments enshrined in its nationally determined contribution (GH-NDCs). The study finds that carbon taxes at much more steeper levels will drive down production from fossil-fuel-based technologies (i.e., thermal electricity) and support renewable like hydro and solar electricity by 2030. However, such steeper rates will yield a negative real growth whereas with a minimal carbon tax rate, the electricity sectors still record some minimal growth as well. A fine balance between growth and curtailment in thermal generation is found around the minimal scenario (Tortoise). On the account of consumer welfare, the urban non-poor have the highest welfare loss followed by the rural poor.

Impact of Emissions Capping on Growth and Welfare

At this point, attention is turned to discuss the implications of quantity restrictions on carbon emissions by a linear quota-ban on fossil-fuel-based electricity production. By the same experiments conducted in the previous section, that is, BAU, Tortoise, Horse, and Cheetah policy scenarios, the analysis here also consider the impacts of incremental restrictions on thermal generation in Ghana's case. As done in the previous section, the differences in impacts on electricity price and demand quantities, government's savings, economic growth, and consumer welfare, all under a competitive market arrangement are discussed. The results are compared with carbon taxes in the foregoing section and conclude on the effectiveness of the two abatement policies.

Model estimation for carbon capping

Here, policy scenarios in relation to emissions abatement targets in Ghana’s updated nationally determined contribution (GH-NDCs) 2021 are, first, presented. As of 2016, Ghana’s total emission about 42.2 MtCO2e which rose to 58.8 MtCO2e by 2019 (EPA, 2022). The country therefore aims to implement 9 unconditional and 25 conditional programmes of action that would cumulatively cut 24.6 MtCO2e and 39.4 MtCO2e by 2030, respectively, compared to the 2020-2030 cumulative emissions in a baseline scenario (MESTI, 2021). The EPA (2022, p81) projects Ghana’s business-as-usual emissions to increase from 42.2 MtCO2e in 2016 to 73.3 MtCO2e by 2030. Based on this, the author conducts four policy experiments on carbon capping in the business as usual (BAU), unconditional, conditional, and rapid cases. Like the previously done in the case of carbon taxation, the unconditional, conditional and rapid scenarios are christened the Tortoise, Horse and Cheetah scenarios, respectively. The emissions cap for each scenario is computed as the ratio of expected total emission growth over the base. That is,

$$E_c = \frac{\eta_e}{\eta_b} \times 100$$

Where η_b is baseline emissions which 42.2MtCO2e; and η_e is total expected emissions by 2030 under each scenario. The absolute emissions are derived from percentage deviation of emissions from the BAU levels by each scenario in question, where E_c is the scenario in question. According to MESTI (2021), Ghana’s ‘Tortoise’ case will reduce emissions by 15 percent below BAU levels by 2030, whereas the ‘ Horse’ scenario will achieve additional 30 percent below BAU level. Hence, a cumulative 45 percent fall in emissions from BAU to the conditional case. Finally, the study introduces a more rapid scenario not contained in the GH-NDC, 'Cheetah' scenario, to gauge the impacts of an extensive tax rate that achieves 95 percent of emissions below BAU level. These are summarized in Carbon caps and the electricity sector

In this section, the study discusses the impacts of carbon caps on the electricity sector in relation to domestic electricity supply, electricity imports, and price of electricity.

Table 7.

Carbon caps and the electricity sector

In this section, the study discusses the impacts of carbon caps on the electricity sector in relation to domestic electricity supply, electricity imports, and price of electricity.

Table 7: Carbon cap scenarios

Experiment	Total emissions MtCO2e	Percentage deviation from BAU levels	Total emissions as a ratio of baseline (42.2 MtCO2e)
BAU	73.3	0%	1.75
Tortoise	62.3	15%	1.48
Horse	40.3	45%	0.96
Cheetah	3.7	95%	0.09

Source: Nkrumah (2024)

Carbon caps and domestic electricity supply

Like environmental taxes, production quotas limit inputs like fossil fuels for thermal electricity which generate scarcity costs and raise the cost of production. As a result, outputs decrease (Figure 17) and, hence, inducing ripple effects in alternate generation technologies and across all sectors of the national economy. The spillover effect on hydroelectricity and on solar generation are largely positive. Thus, greener technologies would step up production to fill in the loss in thermal production, as was also found by

Yoshino et al., (2019). However, it is conspicuous that greener electricity would not sufficiently replace the gap in thermal generation considering the gap between BAU thermal generation and the shortfall in other scenarios.

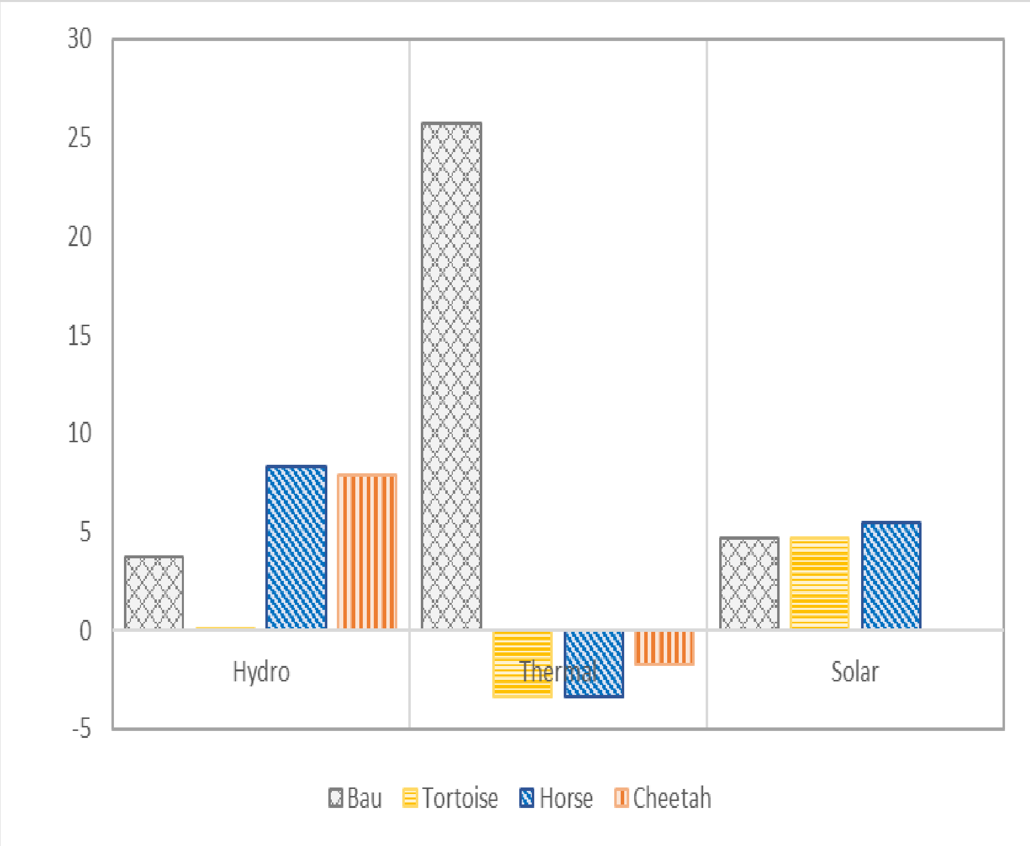

Figure 17: Impact of carbon caps on electricity output
Source: Nkrumah (2024)

Specifically, thermal electricity supply compared to the baseline year increases by about 25 percent in the BAU case where there is no restriction on carbon emissions. But in the other scenarios, production falls by about 4 percent each Tortoise and Horse, and 2 percent for Cheetah. Thus, the impact of capping peaks in the Horse scenario and later falls in the Cheetah case. On the other side, cleaner technologies including hydroelectricity and solar PV rise above baseline levels when carbon capping is introduced on thermal electricity generation.

Carbon caps and electricity imports

Except for the BAU case, electricity imports for both hydro and thermal electricity increase compared to baseline levels (Figure 18).

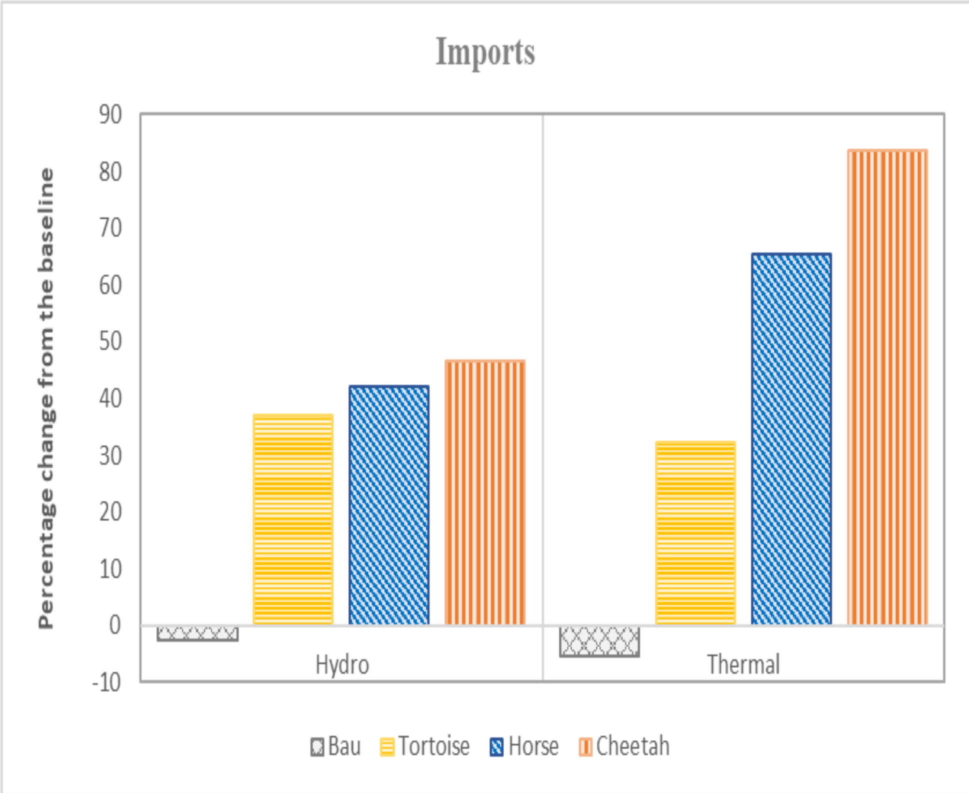

Figure 18: Impact of carbon caps on electricity imports
Source: Nkrumah (2024)

In the first place, thermal generation is curtailed through emissions capping. Hence, extra MWh of electricity would be needed from neighbouring countries to augment the shortfall after hydroelectricity and solar PV generation have ramped up production. This is a reflection of the large contribution of thermal electricity to Ghana's electricity needs with diminishing shares of hydro and solar. Generally, the Ghana's import bill for electricity would rise with tighter caps on carbon emissions.

Carbon caps and price of electricity

Following from above, Figure 19 shows that the final demand price of thermal electricity increases significantly with lower caps in the Horse and Cheetah scenarios.

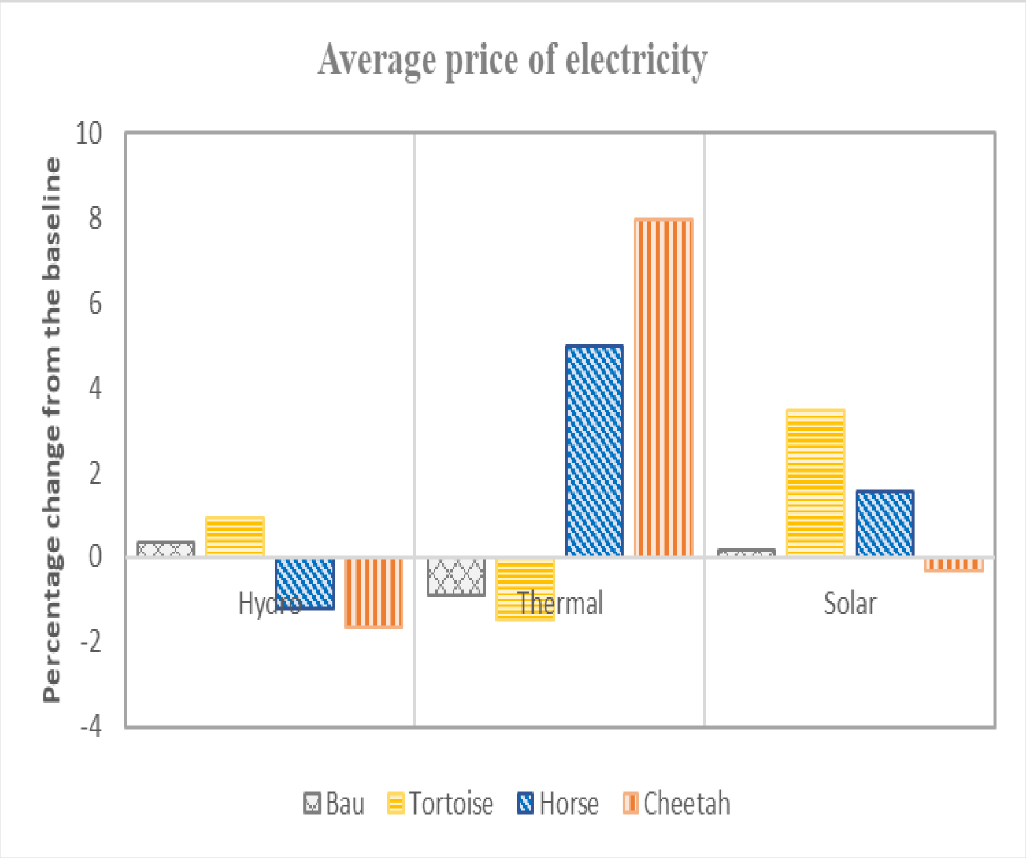

Figure 19: Impact of carbon caps on price of electricity
Source: Nkrumah (2024)

That is, producers would consider to share with consumers the scarcity price necessitated by caps on emissions through the market price. This is unlike the BAU and a milder-cap case where producers absolve the rise in cost of production by caps on emissions. Also, while price of hydroelectricity falls below the baseline, Solar PV rather increases much more significantly. Thus, the weighted average price of electricity by all technologies is expected to increase with higher caps on thermal generation (Mills et al., 2019). The rising price of electricity is from declining thermal electricity supply over the base-year and limited uptake in alternative technologies (Figure 17), and a rise in imports (Figure 18).

Carbon caps and government's fiscal balance

Unlike carbon taxes, capping policies do not generate additional government revenue to subsidize cost spillovers from tighter restrictions on production, hence the decline in revenue and a rise in negative government savings (Figure 20). Specifically speaking, government savings decline monotonically from the BAU to a tighter cap in the Cheetah scenario.

Overall, revenue outperforms expenditure only up to a minimal cap in the Tortoise Scenario. Beyond that, government expenditure outweighs revenue leading to negative government savings (see Figure 20). It is for this reason that authors like Fremstad and Paul (2019) have argued that emissions-targeting polices can only become attractive if they support domestic revenue mobilisation that could be used to foster growth and other related sustainable development goals.

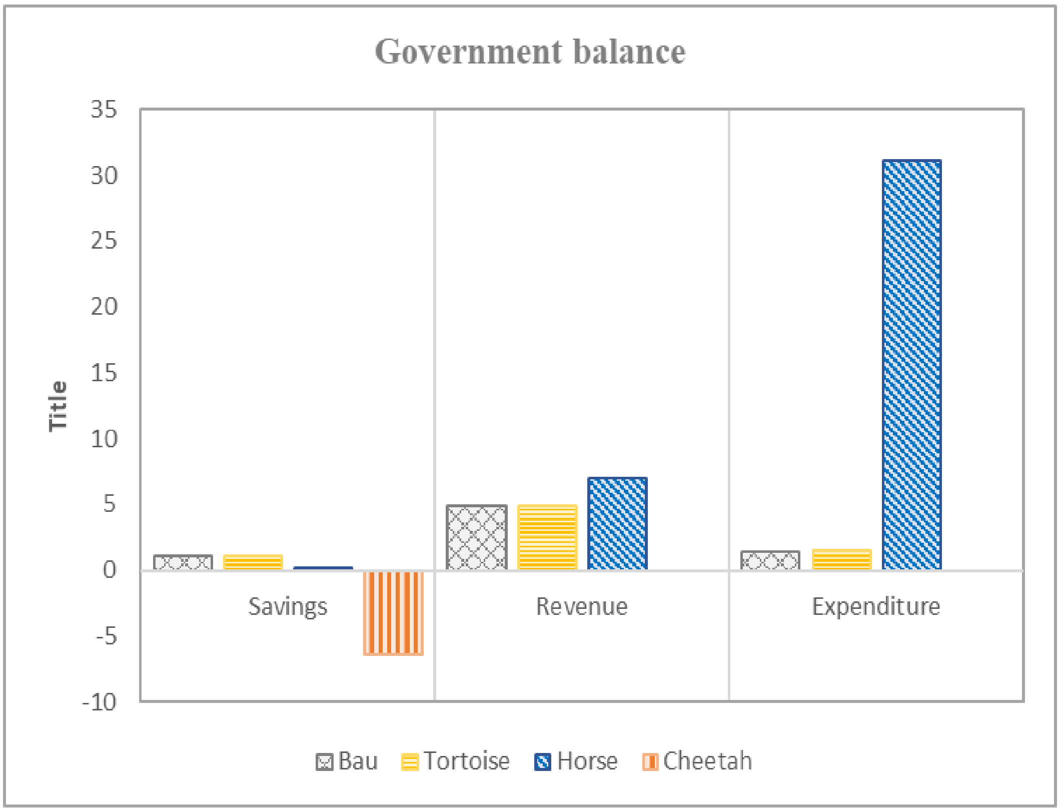

Figure 20: Impact of carbon caps on government's balance
Source: Nkrumah (2024)

Carbon caps and economic growth

The interlinkages between the electricity sector and the rest of economic sectors cannot be overemphasized. Thus, a carbon cap on thermal electricity production will have impacts on economic growth and welfare. In Figure 21, the study shows this impact on economic growth through aggregate demand. The share of absorption and indirect taxes increase significantly in the Tortoise case by around 80 and 112 percent, respectively, over the baseline. This is respectively followed by the Horse and Cheetah scenarios. However, due to higher share of imports and lower exports, economic growth rate generally decreases from about 3.5 percent in BAU to 1.12 percent and further down to 0.78 percent growth in the Cheetah Scenario.

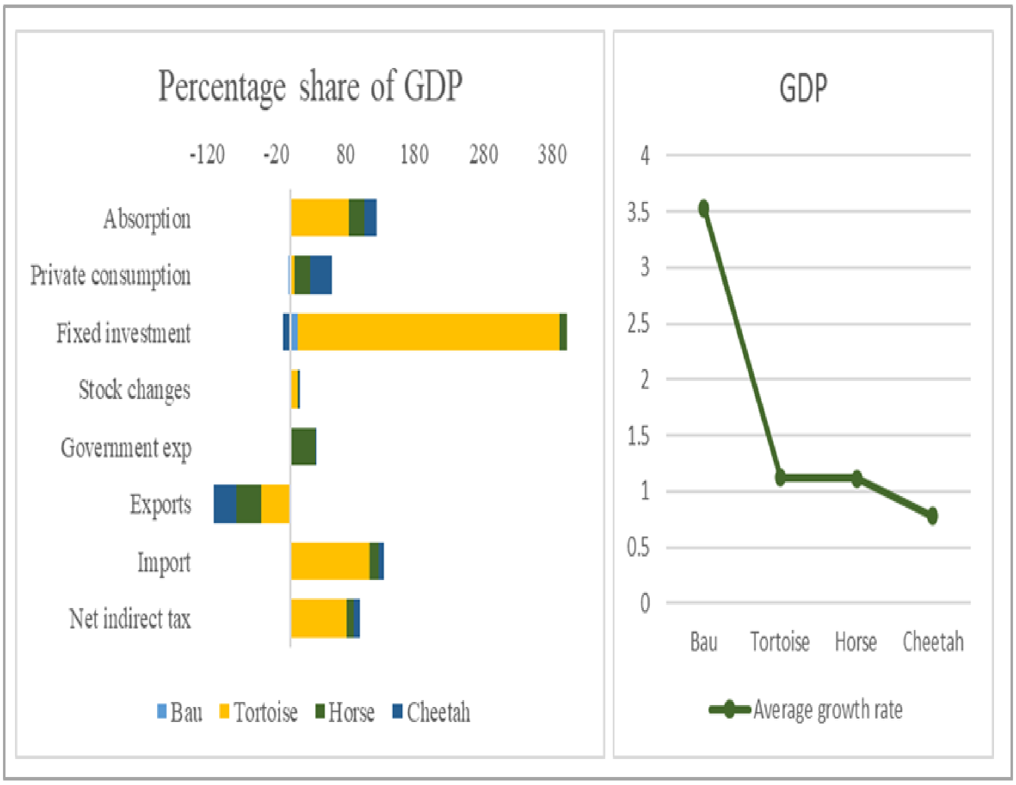

Figure 21: Impact of carbon caps on economic growth
Source: Nkrumah (2024)

This implies, a carbon capping policy will cut more than 2 percent in growth, even with a minimal cap rate, and nearly 3 percent of economic growth forfeited for a tighter cap as in the case of the Cheetah Scenario.

Additionally, the study compares nominal and real growth over the base-year across the economic sectors in Figure 22. It is observable that, the agriculture sector, except food, and mining and quarry sectors experience negative growth in nominal GDP together with thermal electricity sector. This is because these sectors, especially mining sectors, rely on embedded thermal technologies that burn fossil fuels to generate electric power. The negative spikes in nominal growth also signify the adverse effect of general price hikes precipitated by emissions capping on the sectors vulnerable to electricity price shocks.

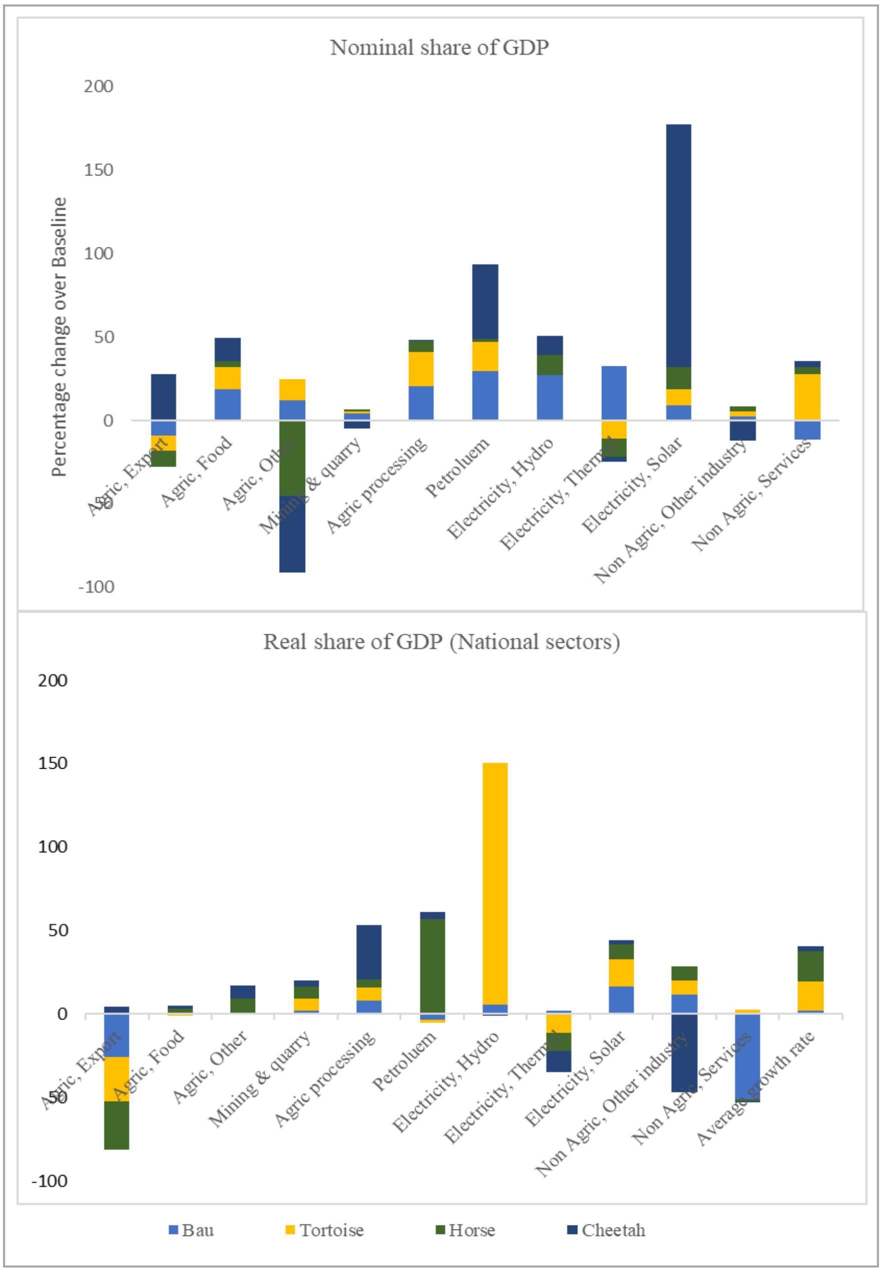

Figure 22: Impact of carbon caps on sectoral growth
Source: Nkrumah (2024)

In the electricity sectors, growth in thermal electricity declines after the BAU case, whereas hydroelectricity and solar PV generation grows significantly, especially in the Cheetah Scenario. On the other hand, agriculture exports, other non-agriculture industry and services experience negative growth in real GDP below the baseline. Most conspicuously, hydroelectricity has the most significant real growth almost wholly by the Tortoise Scenario. Solar electricity, on the other hand, which had very high nominal growth of about 150 percent shrinks to less than 50 percent jump in growth at constant prices.

Carbon caps and consumer welfare

Lastly, Figure 23 presents the consumer welfare implications of emissions capping. The study measures welfare as an equivalent change in the income of a consumer to accept or on a new equilibrium after a price change. The incidence of welfare changes is therefore discussed based on Figure 23. In the first place, poor urban households have the highest incidence of welfare loss in both the Tortoise and Horse Scenarios, about 35 percent change in income is required when emissions capping is implemented. They are followed by rural poor and non-poor households. It is worthy of notice from Figure 23 that the rural poor will be greatly affected in very emissions capping policies.

The urban non-poor households are the least affected due to smaller share of electricity consumption compared to other households. Also, apart from the BAU case, rural households have higher changes in welfare than the urban households, except for the urban poor. More broadly, tighter carbon caps induce higher welfare changes for consumers. This is unlike carbon taxes that could generate revenue to cushion aggregate demand and support households, emissions capping has no such fiscally neutral arm (Bergh & Botzen, 2020; Franks et al., 2018). Hence, welfare burden increases for the most vulnerable, especially the urban poor who is without fiscal support.

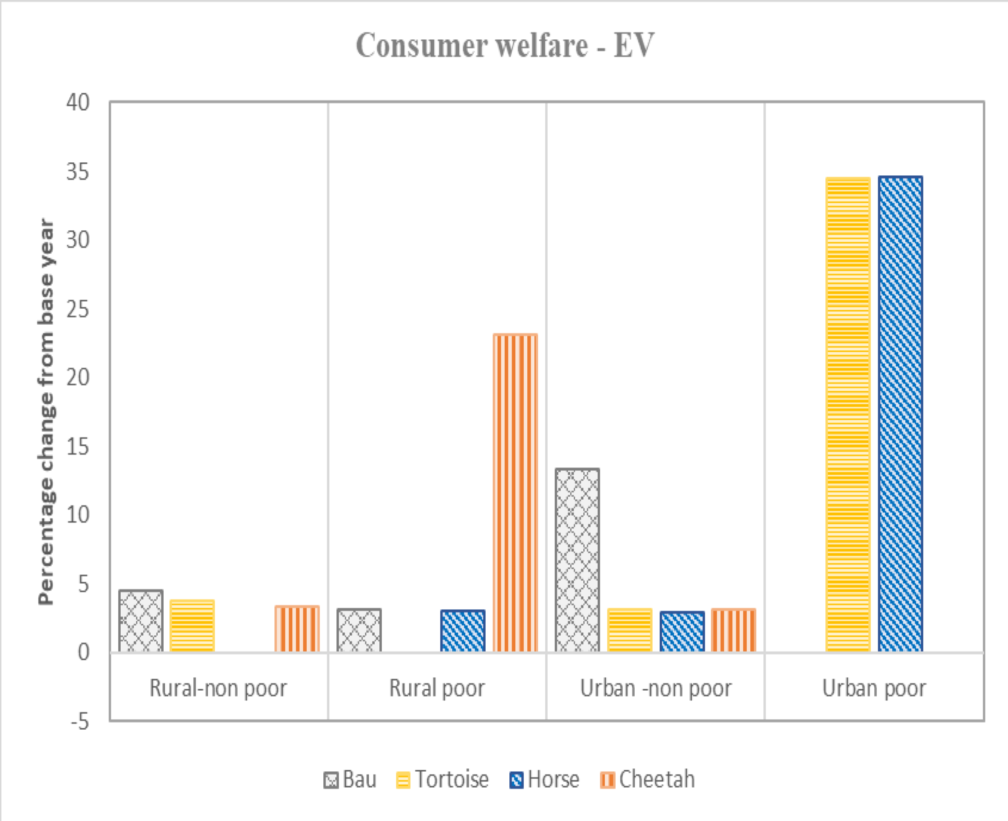

Figure 23: Impact of carbon caps on consumer welfare
Source: Nkrumah (2024)

In sum, this study assessed the impacts of carbon caps policy in thermal electricity generation on economic growth and the general electricity sector. In the foregoing analysis, the author has documented evidence of graduated impacts from carbon caps for graduated levels carbon caps. The study has shown that higher caps will decrease production from fossil-fuel-based technologies (i.e., thermal electricity) and, at the same, time increase production from greener technologies like hydro and solar electricity by 2030. Despite these primary successes, steeper caps yield an adverse economic growth and rising burden on the poor, especially in the urban centres and the rural poor. Because caps alone do not generate commiserate revenue, government savings is adversely affected due to decreases in final goods and services in the national economy.

Impact of Renewable Feed-in-Tariff on Growth and Welfare

At this point, results of the simulation exercise examining the impacts of REFITs in the residential demand sector on government revenue as well as consumer welfare are presented and discussed. Towards the end, the opportunity cost of 'no-action' is also presented. This assesses the equivalence of megawatt hours of electricity and carbon savings forfeited if no REFITs nor any alternative policy were implemented between 2013 to 2030. Before the results from the simulation on revenue and welfare are discussed, The study opens with a section on description of relevant features of Ghana's residential demand sector.

Descriptives analysis of residential electricity sector in Ghana

Total expenditure per capita

To begin, the study shows in Figure 24 the distribution of household consumption expenditure per capita over the period as a bedrock to understanding electricity demand patterns in Ghana's residential sector. It could be seen the chart that per capita expenditure, generally, increases over the historical period, that is 2013 – 2021, although the first 3 years saw a gentle decline due to dampened economic growth brought about by the 2013 – 2016 power crisis (Kwakwa, 2021). Also, the projected period, 2022 – 2030, witnesses a rising expenditure per capita, most especially in an accelerated economic growth (AEG) case. In all these, the most distinguishable pattern is the wide disparity in incomes between consumers within the higher brackets and their counterparts at the bottom. As shown in Figure 24, this becomes more pronounced in the AEG case signifying that a greater share the country's growth would accrue to higher income household than the poor ones.

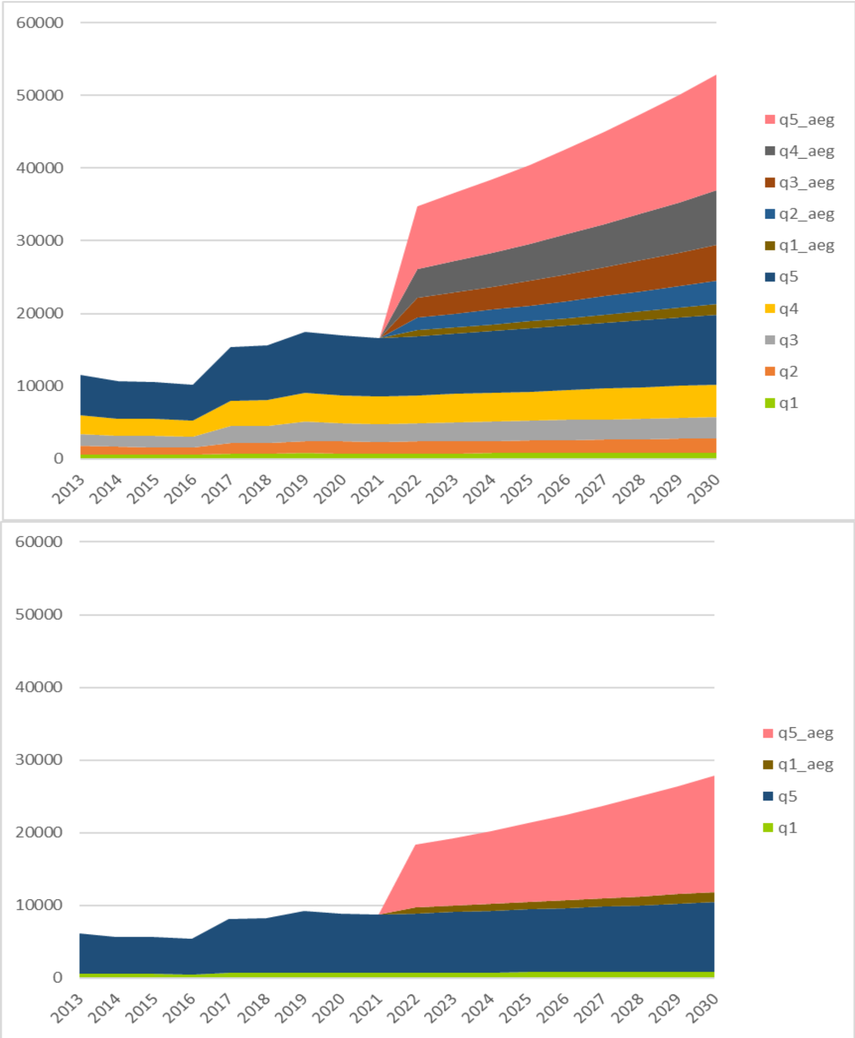

Figure 24: Total expenditure per capita
Source: Nkrumah (2024)

Per capita consumed quantities of electricity

Electricity demand is a positive correlate with income (Sadraoui et al., 2019). Thus, consumers in higher income brackets tend to consume more compared with those with lower incomes. Ghana's residential electricity demand sector, like most countries in sub-Saharan Africa, is characterised by wide dissimilarities in consumption between consumers especially between the top and bottom 20 percent of households by income standards. This gaping disparity, measured in terms of expenditure per capita, is specially isolated in Figure 25.

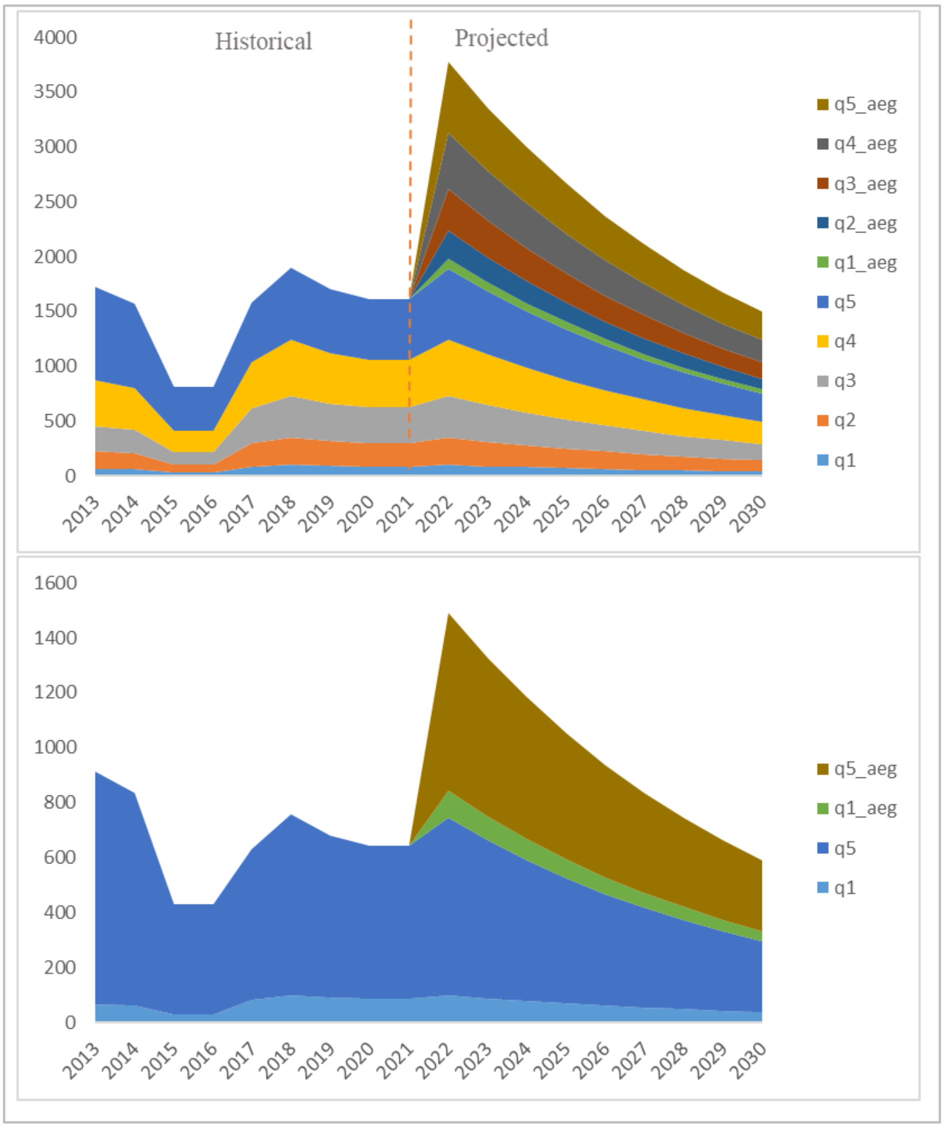

Figure 25: Per capita consumed quantities of electricity
Source: Nkrumah (2024)

A closer look at Figure 25 shows a sharp decline in demand from 2013 to 2016. This coincides with the period where the country experienced its worst power supply crisis, locally referred to as "Dumsor" (Kwakwa, 2021). In those years, consumers in higher income brackets had higher dips in electricity consumption.

But after 2016 when grid stability was restored, consumers with higher purchasing powers increased consumption for 2 years and began a dive from 2019 to 2021. The downturn from 2019 could be attributed to income shortfalls due to economic challenges exacerbated by COVID-19 and the

Russia-Ukraine conflict. A projection up to 2030, however, indicates that electricity consumption per capita peaks in 2022, sharper in an accelerated economic growth (AEG) scenario, and falls as a result of general financial hardships and government's austere measures currently being implemented in Ghana under an IMF bailout package for the country (Hlovor, 2023; Ntim & Botchway, 2023).

Expenditure share of electricity consumption

Following from the two charts above, the consumption shares of electricity by households rose during the years of the power crisis: 2013 – 2016 (Figure 26). This could be plausibly explained by a combination of two reasons. The first is households' reprioritisation of needs and the second being households experiencing reduced incomes from low economic growth. That means households reorganized their consumption needs to accommodate more demand for electricity in the face of supply shortfalls by reducing or eliminating other household goods and services.

The other reason could be that the reorganisation of households' needs may have been reinforced due to lower income growth caused by the power crisis (see Figure 26).

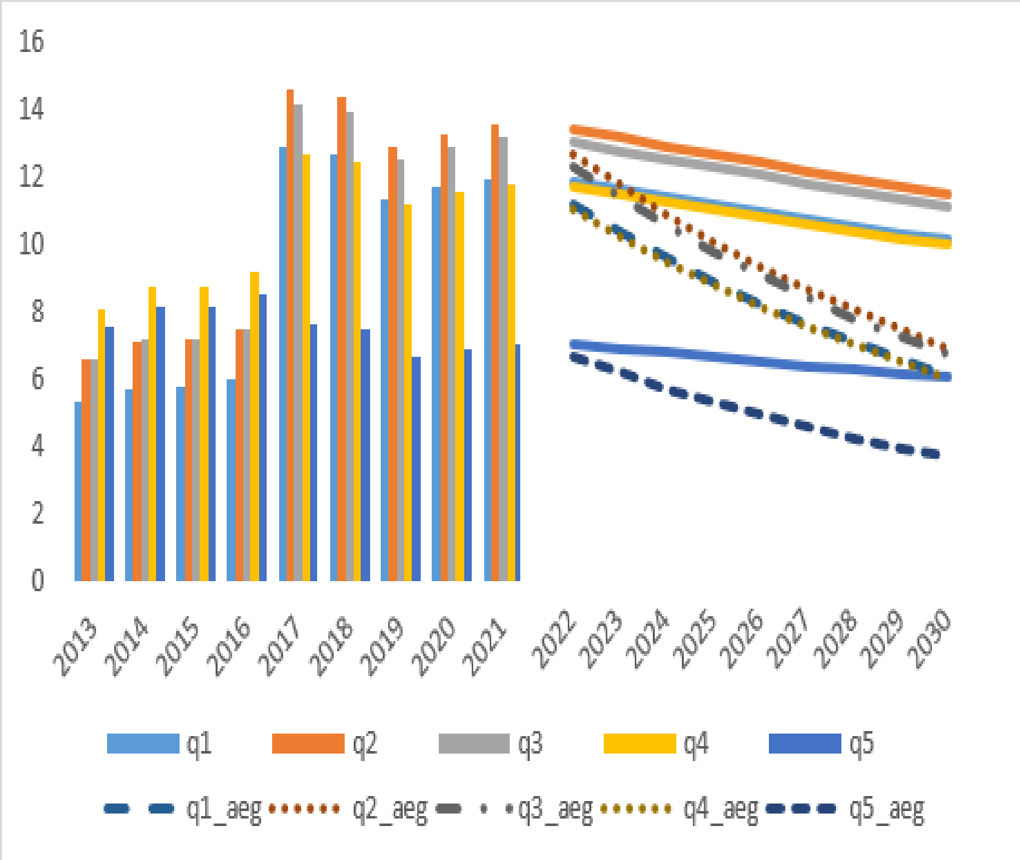

Figure 26: Expenditure share of electricity
Source: Nkrumah (2024)

When power supply was restored, share of electricity rose significantly for all households, fell in 2019, and marginally rose afterwards to 2021 when, again, the twin crisis of COVID-19 pandemic and conflict in eastern Europe struck crisis (refer to Figure 26). A further projection shows a gentle decline in expenditure share of electricity in business-as-usual growth scenario but a much steeper decline in the accelerated economic growth case. The fall in consumption shares is due to falling per capita consumption units of electricity and rising income/expenditure per capita.

Model estimation for REFITs

As stated earlier, the simulation exercise is conducted using the SUBSIM model which computes distributional impacts of demand price changes on consumer welfare and government revenue. The SUBSIM is implemented in the STATA (version 17) software. The analytical process is illustrated in Figure 27.

Ghana's electricity market operates an increasing-block tariff regime with categorizes residential consumers on four (4) bands per a billing cycle: (1) 0-50KWh, (2) 51-300KWh, (3) 301-600KWh, and (4) above 600KWh. The framework translating electricity price changes through REFIT to final distributional impacts are in Figure 27. The final electricity tariff which is combination of energy charge, levies (streetlight and national electrification), and some subsidies for lifeline consumers (0-50KWh). The energy charge includes a REFIT mark-up. The size of the REFIT mark-up is determined by the share of renewable electricity on the national grid. The study, therefore, experiments with Ghana's target of 10 percent renewable electricity penetration contained in the Ghana's Nationally Determined Contribution (GH-NDC) 2015-2020 under the Paris Agreement, which was later updated to 2030 (MESTI, 2021).

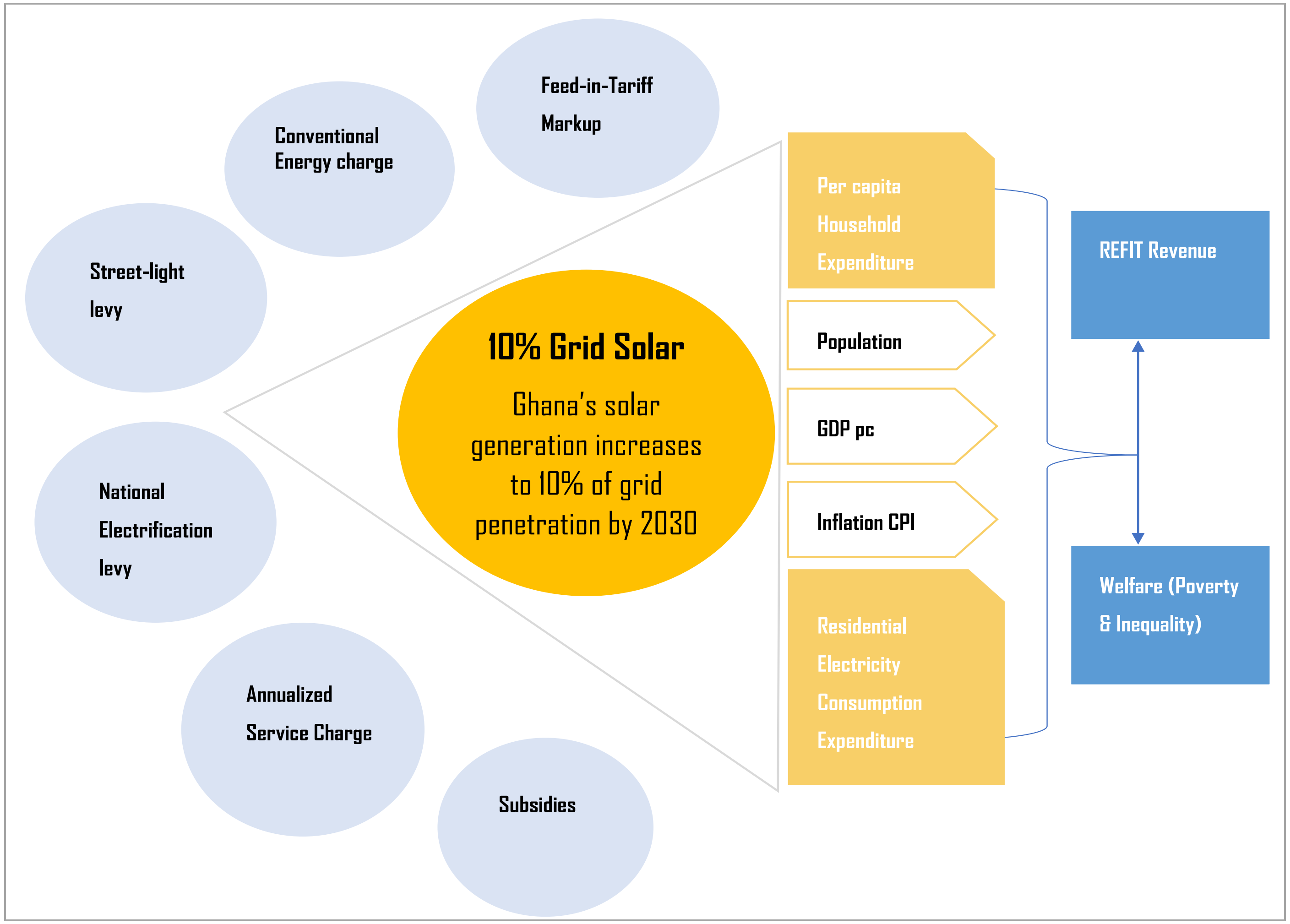

Figure 27: Framework for the distributional impacts of REFITs
Source: Nkrumah (2024)

Uprate of consumption and poverty benchmarks

The simulation exercise is implemented for a period of 15 years, 2016-2030, using the GLSS 7 expenditure survey conducted in 2016/17. In this regard, per capita household expenditure and absolute poverty line are uprated using GDP and CPI, respectively. Additionally, GDP and CPI growth rates after 2022 are uniformly distributed based government of Ghana's forecasts. Household size is deemed to remain at four per household till 2030 whereas household population is increased yearly based on population estimates by the Ghana Statistical Service.

Simulated impacts of REFITs

REFITs and government revenue

Turning the attention to the main simulation results, the analysis opens by discussing the simulated impacts of REFITs on revenue. This is often of first importance when considering REFITs as a revenue stream to finance electricity production using renewable technologies. As will be shown later in Table 8, the simulated revenue accrued from the REFIT policy between 2013 – 2030 amounts to about GHS 21million. It is also shown in the same table that higher solar PV penetration rate corresponds to higher revenue for REFITs. A greater portion of the total revenue is realised after 2021. This is due to expected rapid growth, coupled with higher penetration rate of solar PV over the next decade.

Additionally, the level of increase in prices peak at graduated revenue thresholds as years increase (Figure 28). Marginal revenue from REFITs peak about GHS 40,000 in 2013. This doubles in about a decade to about

GHS80,000 by 2021 in nominal terms. By 2030, the revenue threshold hits about GHS 1.5million.

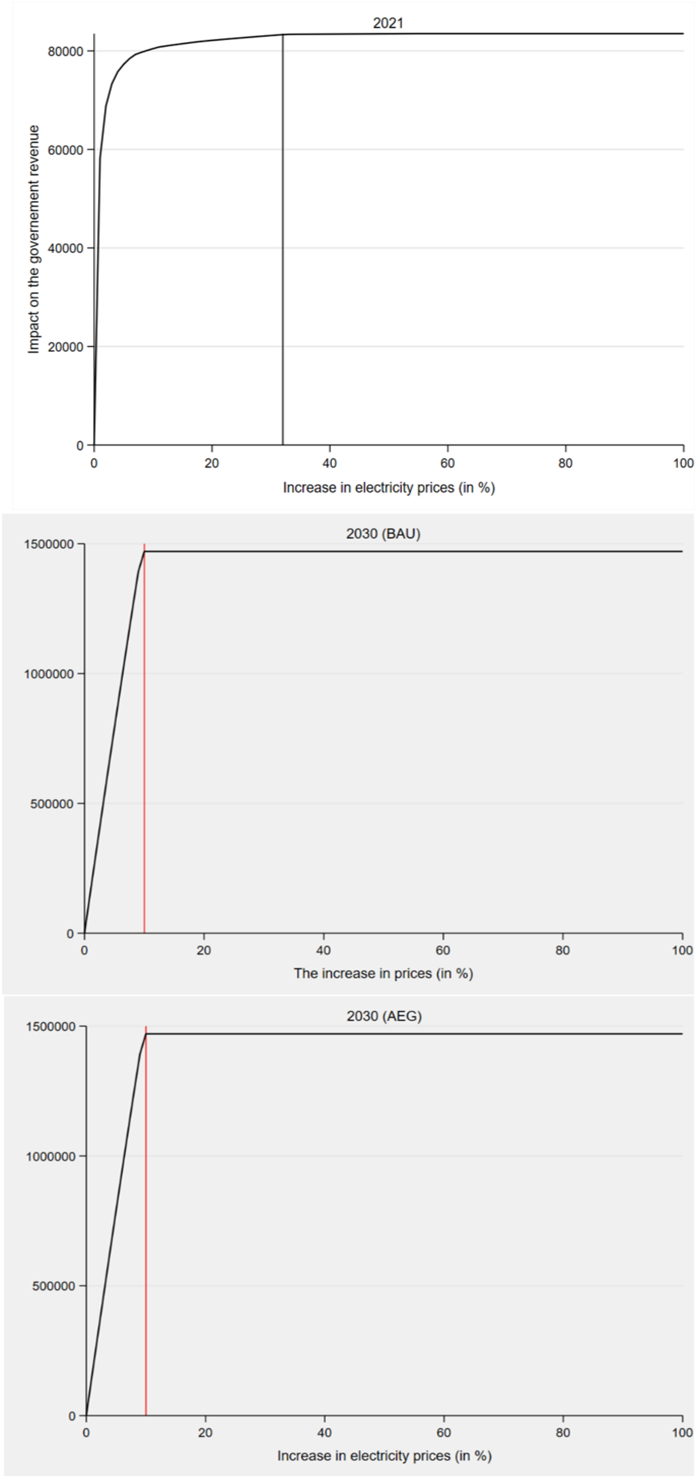

Figure 28: REFIT Revenue threshold by level of price change
Source: Nkrumah (2024)

While the thresholds are increasing, the optimal change in price (shown with the red line) decreases as the year increased move from 2013 to 2030, from about 40 percent in 2013 to about 10 percent in 2030. This implies that as years go by, a smaller change in price yields higher impact on revenue than previously, possibly due to higher demand from residential consumers. It is important to point out that the movements in marginal revenue from price changes are as a result of increased penetration of solar generation and increased demand for electricity by residential consumers.

REFITs and consumer welfare

Often, a counterargument against REFITs is prominently raised regarding the impacts they generate on consumer welfare through increases in energy prices (Lagac & T Yap, 2020; Winter & Schlesewsky, 2019). Therefore, it is always insufficient to only consider the cashflow of renewable energy investments funded through REFITs. Apart from the top quintile group (Q5) (deep blue line), REFITs generally have an adverse, downward sloping impact on welfare of residential consumers (see Figure 29). The outlier Q5 consumers are, however, not negatively affected because expenditure share of electricity consumption is smallest compared to other household groups. The study isolates the welfare impacts on the top (Q5) and bottom 20 percent (Q1) on the right pane of Figure 29.

It is further evident that consumer welfare for Q1 – Q4 worsens drastically between 2016 and 2017. This is underscored by a major REFIT review in 2016 which saw huge jump in tariffs making Ghana one of the few countries in Africa with higher REFITS (IRENA, 2022). But after 2017, consumer welfare becomes less affected. In a rapid growth (AEG) scenario, the negative effects of REFITs are reduced even more drastically compared to a BAU case.

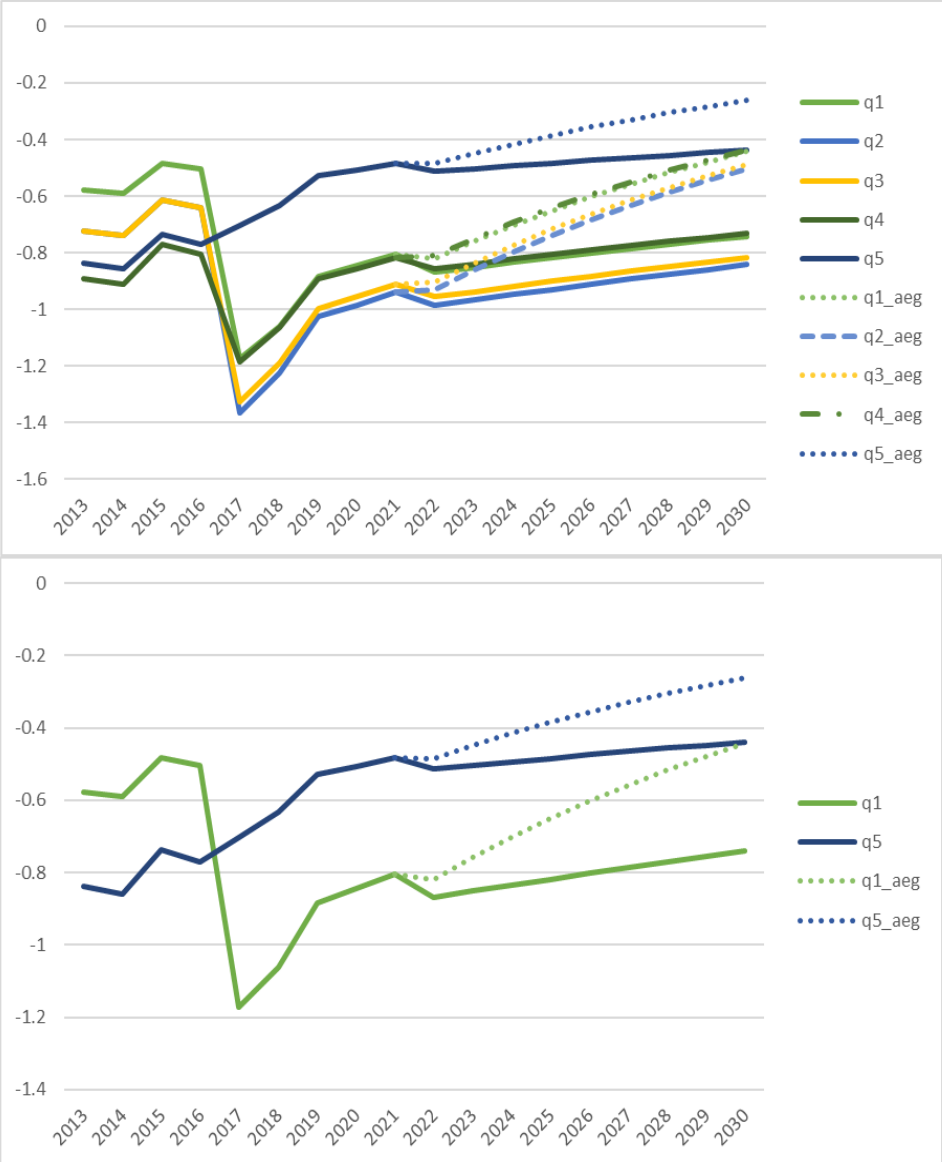

Figure 29: Impact of REFITs on consumer welfare
Source: Nkrumah (2024)

It is even more interesting to know that benefits of an accelerated growth will inure more to the poorest 20 percent (Q1), from about -0.8 to -0.4 which represents about 100 percentage points improvement in welfare than the higher quintile (Q5) consumers. This indicates that REFIT, like any other price-focused policy, is less harmful to consumer welfare during times of higher income growth (Finon, 2019).

Level of household transfer and welfare

To mitigate the impacts of REFITs on consumers, governments worldwide provide fiscally neutral transfers to supports vulnerable households. In Figure 30, the study shows the level of transfer required to ease the adverse distributional impacts of price increases on consumer welfare. Due to the inequalities in incomes, a cedi transfer to all households will have varying welfare impacts on different households. This is illustrated in Figure 30 where different households by quintile groups have different welfare intercepts and slopes; the poorer households have lower intercepts and gentle slopes. Because of this, the level of transfer that will make the poorest households indifferent to price changes (shown by the red line) is smaller compared to the level of transfer that will neutralize the welfare loss for the richer quintiles.

That is, while households in Q1 require to be compensated with less than 30 percent of the unit price change, the Q2 group will need almost 100 percent of the price change, and so forth. Households in higher quintiles benefit from transfers if the level of transfer as a percentage of the price change is substantial. Also, in Figure 30 the level of compensation to the poorest households increases between 2021 and 2030 by more than 5 percentage points to about 40 percent of the unit price change due to REFITs.

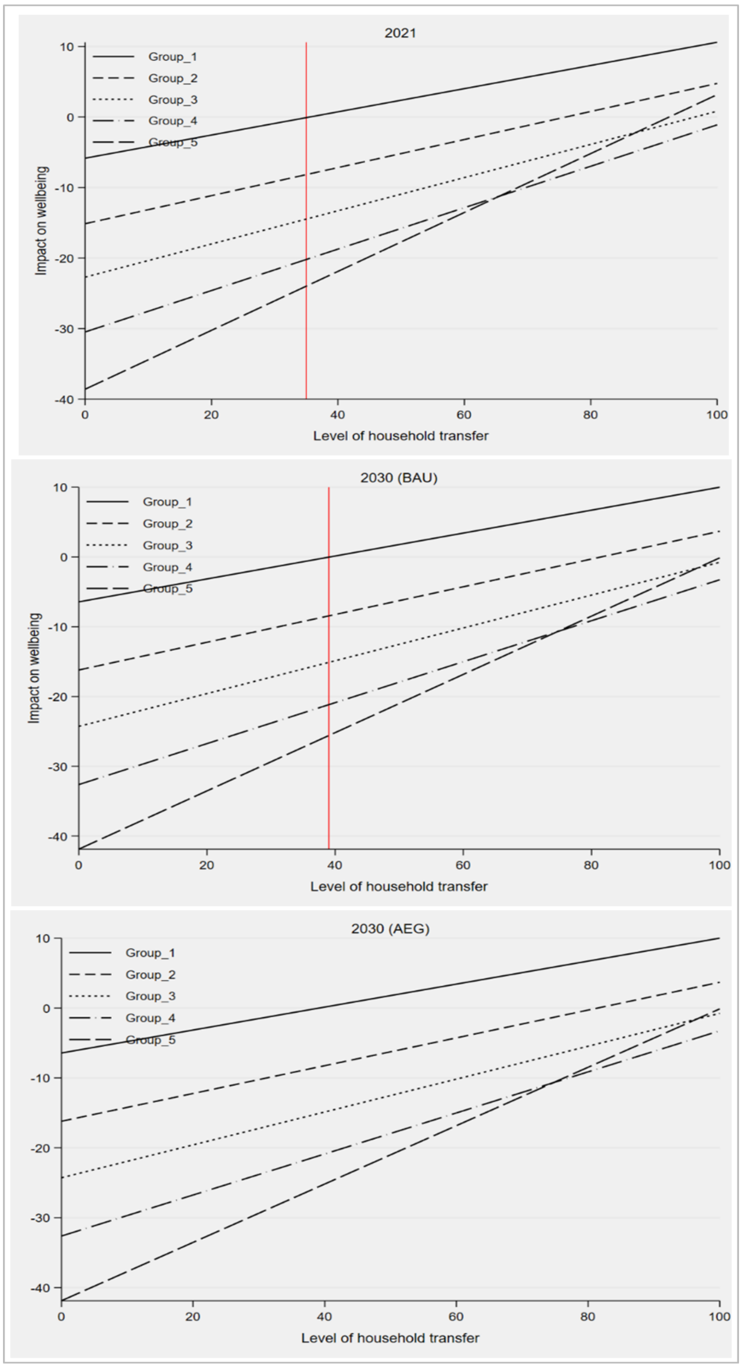

Figure 30: Level household transfer and consumer welfare
Source: Nkrumah (2024)

Opportunity cost of 'no action'

Finally, the study discusses the opportunity cost of no policy action regarding renewable energy production up to 2030. This is intended to quantify what the country would miss if there is no REFIT to fund renewable energy generation nor any alternative that achieves same. This is particularly relevant in guiding policy dialogue whenever there is a proposal to scrap REFITs. At the moment, Ghana has abandoned its REFITs from in its amended Renewable Energy Act 2020 which seeks to replace REFITS with competitive tendering processes and auctions. Yet, institutional structures and processes are yet to laid to facilitate competitive procurement processes. Hence, the aim of measuring the cost of no-action in adding new units of renewables unto the grid up to 2030.

In Table 8, the author presents the simulated revenue from REFITs from 2013 to 2030. This is converted to US dollars at an average exchange rate of GHS 11 to the dollar. The analysis still holds for any chosen exchange rate for the three-decade period. The weighted average levelized cost of electricity (LCOE) of solar PV obtained from (IRENA, 2023) is used to convert the accrued revenue to units of solar electricity forgone. Also, the author quantifies the carbon savings forgone. The results displayed in Table 8 shows that the country stands to forfeit up to 6.33MW of solar electricity and 0.27 metric tons of carbons savings if no renewables were not introduced from 2013 to 2030. Between 2021 to 2030 alone, a total of 5.1WM of solar electricity and 0.21MtCO2 of carbon savings would be forfeited after scraping REFITs without an alternative renewable energy investment.

Table 8: Computation of opportunity cost of no-action

Year	Total Revenue[4]	US$1=GHS 11	Average weighted Levelized cost of electricity (LCOE) of solar PV ($/KWh)[5]	Units of electricity from solar PV foregone			Grid Emissions Factor[6] for solar/wind (tCO2/MWh)	Grid Emissions Factor for all other projects (tCO2/MWh)	Net Grid Factor[7]	Carbon savings forgone[8] (tCO2)
				KWh	MWh	MW[9]				
2013	1041442	94676.55	0.18	528919.25	528.92	0.06	0.35	0.46	0.11	0.007
2014	984805.4	89527.76	0.16	549250.08	549.25	0.06	0.32	0.36	0.04	0.003
2015	771421.6	70129.24	0.12	579580.47	579.58	0.07	0.28	0.31	0.03	0.002
2016	771421.6	70129.24	0.11	661596.57	661.60	0.08	0.39	0.43	0.04	0.003
2017	1360218	123656.18	0.08	1472097.40	1472.10	0.17	0.43	0.47	0.04	0.007
2018	1290453	117313.91	0.07	1652308.58	1652.31	0.19	0.46	0.53	0.07	0.013
2019	1194911	108628.27	0.06	1752068.91	1752.07	0.20	0.39	0.45	0.06	0.012
2020	1105586	100507.82	0.06	1827414.88	1827.41	0.21	0.36	0.4	0.04	0.008
2021	1031378	93761.64	0.05	1953367.42	1953.37	0.22	0.36	0.4	0.04	0.009
2022	1300572	118233.82	0.04	2822421.88	2822.42	0.32	0.36	0.4	0.04	0.013
2023	1284814	116801.27	0.04	3194840.95	3194.84	0.36	0.36	0.4	0.04	0.015

[4] Simulated revenue from REFIT based on the SUBSIM model

[5] Levelized cost of electricity from solar PV (IRENA, 2023). After 2021, the author holds constant the 13 percent year-on-year change from 2021 to 2022 in LCOE for solar till 2030.

[6] Grid emission factor is the amount of CO2 emitted per unit of electricity generated and supplied into the national electricity grid (Ministry of Power, 2015). The emissions factor is reported by the energy regulator up to 2021. Hence, the study assumes the same share for 2022 to 2030.

[7] Net grid emissions factor measures the net emissions from renewable sources

[8] Carbon savings foregone is the amount of CO2 forfeited for not non-production of renewable electricity to replace the conventional grid electricity

[9] Annualized megawatts hour MW = MWh/8760 hours

2024	1270773	115524.82	0.03	3620748.94	3620.75	0.41	0.36	0.4	0.04	0.017
2025	1258274	114388.55	0.03	4107968.54	4107.97	0.47	0.36	0.4	0.04	0.019
2026	1247132	113375.64	0.02	4665366.44	4665.37	0.53	0.36	0.4	0.04	0.021
2027	1237196	112472.36	0.02	5303142.50	5303.14	0.61	0.36	0.4	0.04	0.024
2028	1228363	111669.36	0.02	6033133.96	6033.13	0.69	0.36	0.4	0.04	0.028
2029	1220487	110953.36	0.02	6868641.54	6868.64	0.78	0.36	0.4	0.04	0.031
2030	1213483	110316.64	0.01	7825153.10	7825.15	0.89	0.36	0.4	0.04	0.036
Total	**20812731**	**1892066.40**		**55418021.40**	**55418.02**	**6.33**	**6.58**	**7.41**	**0.83**	**0.266**

Source: Nkrumah (2024)

Model Robustness and Sensitivity

The computation modelling conducted in this study has been rigorous and yields consistent results mimicking the exact economic structure and workings of the Ghanaian economy in the base year. Indeed, a simple back-of-envelop calculation of GDP from the macro-SAM presented in Tables A1 to A3 reveal consistent estimates from expenditure (GHS 164.02 billion), net taxes of GHS 16.43billion and value-added at basic prices (GHS 147.59 billion). The congruence of GDP estimates from different approaches asserts the robustness of the calibrated model. Also, a scrutiny of sectorial and factorial output shares for the base year gives same conclusion. For example, Ghana’s economy as of 2015 was dominated by the services sector, with commanding 40 percent value-added share, about 55 percent of total employment. Value-addition in the agriculture sector contributes less than a quarter to GDP, and so forth.

Furthermore, simulations carried out in this study were principally done in comparative-static framework (snapshots of the model codes in GAMS studio have been displayed in the appendix). A comparative-static CGE framework does not consider how the present evolves into the future through influences from the past. Technically, one is unable to see the change-pathways in-between time when the before-and-after periods are quite apart. This assumes away any structural change that may occur between the two states, including economic uncertainties that could significantly alter the existing economic structure.

For instance, changes in world prices of fossil fuel can have influences on the domestic price of fuel in thermal electricity generation and the consequently the share in the energy mix. This will have implications on the effect size of carbon taxes and cap restrictions relative to the baseline. Similarly, weather variations can affect the feasibility of solar PV REFIT scheme. Although the increasing illumination of the earth's surface and rising temperature is rather favourable for solar PV penetration, hydroelectricity which provides baseload power becomes highly susceptible to weather variations. Hence, given the intermittent nature of solar PV generation, grid electricity becomes highly unstable with increasing penetration for solar PV and REFIT schemes. Additionally, capital accumulation and technical progress can alter the production efficiency and cut wastes such as carbon emissions. Further, population and labour force growth rates also have the tendency of altering household composition, labour supply and income distribution. All of these are typically missing in static models.

Nonetheless, static CGE models are still useful because, as conducted in this study, the period between 2015 and 2030 is not so long a time for Ghana to undergo major structural shifts. In fact, currently in 2024, Ghana's economy remains fundamentally unchanged from 2015 economy, taking away the power crisis at the time. Hence, by comparing what Ghana seeks to achieve by 2030 to the baseline in 2015 is quite a plausible thing to do.

Chapter Summary

A carbon tax as an innovative environmental policy tool is potent to limit carbon emissions from fossil fuel combustion in thermal electricity generation. It forms part of the broader carbon pricing tools. Although governments globally are gravitating towards more efficient carbon pricing systems, including emissions trading systems (ETS), carbon taxes remain most dominant and most appealing due to the simplicity in its administration by governments worldwide, especially in less developed countries. This tax, mostly applied in the electricity to internalise social costs of carbon emissions in the generative activities in the energy market. Notwithstanding, this simple tool may, however, come with attendant welfare implications.

The specific objective was to assess the impacts of carbon taxes on economic growth and the electricity market using scenarios built on Ghana's commitments enshrined in its nationally determined contribution (GH-NDCs). The study found that carbon tax at much higher levels will reduce output from thermal electricity and support renewable electricity by 2030. However, at such steeper rates, there will be negative real growth whereas with a minimal carbon tax rate, the electricity sectors still record some minimal growth as well. A fine balance between growth and curtailment in thermal generation is found around the minimal scenario (Tortoise). On the account of consumer welfare, the urban non-poor have the highest welfare loss followed by the rural poor.

Also, the study has demonstrated the implications of quantity restrictions on carbon emissions by a linear quota-ban on fossil-fuel-based electricity production. By the same experiments conducted in the previous section, that is, BAU, Tortoise, Horse, and Cheetah policy scenarios, the study measures the impacts of incremental restrictions on thermal generation in Ghana's case. As done in the previous section, the author shows the differences in impacts on electricity price and demand quantities, government's savings, economic growth, and consumer welfare, all under a competitive market arrangement. The study compares the results with carbon taxes in the foregoing section and conclude on the effectiveness of the two abatement policies.

In the foregoing analysis, the author documents evidence of graduated impacts from carbon caps for graduated levels carbon caps. The study has therefore shown that higher caps will decrease production from fossil-fuel-based technologies (i.e., thermal electricity) and, at the same, time increase production from greener technologies like hydro and solar electricity by 2030. Despite these primary successes, steeper caps yield an adverse economic growth and rising burden on the poor, especially in the urban centres and the rural poor. Because caps alone do not generate commiserate revenue, government savings is adversely affected due to decreases in final goods and services in the national economy.

Lastly, in this study, the author has analysed the rapidity of penetration, revenue and economic impacts of REFITs for solar electricity in a developing Africa country using Ghana as a case-in-point. In this section, the analysis showed the simulated impacts of REFITs on residential electricity demand, revenue, economic growth, and consumer welfare. The simulated revenue accrued from the REFIT policy between 2013 – 2030 amounts to about GHS 21million. It is also shown in the same table that higher solar PV penetration rate corresponds to higher revenue for REFITs. A greater portion of the total revenue is realised after 2021. This is due to expected rapid growth, coupled with higher penetration rate of solar PV over the next decade.

Nonetheless, REFITs have an adverse, downward sloping impact on welfare of residential consumers. Due to the inequalities in incomes, a cedi transfer to all households will have varying welfare impacts on different households. That is to say, households in higher quintiles benefit from transfers if the level of transfer as a percentage of the price change is substantial. As the opportunity cost of no-action, Ghana stands to forfeit up to 6.33MW of solar electricity and 0.27 metric tons of carbons savings if no renewables were not introduced from 2013 to 2030. Between 2021 to 2030 alone, a total of 5.1WM of solar electricity and 0.21MtCO2 of carbon savings would be forfeited after scraping REFITs without an alternative renewable energy investment.

CHAPTER FIVE

SUMMARY, CONCLUSION AND POLICY IMPLICATIONS

Finally, this last chapter presents the summary of the research, including summary of findings, conclusions and policy implications of the study. In addition, the study discusses the limitations of the present study and how they were managed to arrive at consistent and unbiased research findings. The identified limitations are proposed as areas for future studies.

Summary

This study has attempted to measure the impacts of transition in the electricity sector using Ghana's case for the developing world. The author has sought to unravel the economic impacts in transition pathways to inform holistic policy planning. The first specific objective sought to compute the impacts of a carbon tax policy on economic output and economic welfare by simulating three incremental but hypothetical scenarios of tax rates relative to the conditional and unconditional carbon-abatement commitments contained in Ghana's updated GH-NDCs for 2020-2030.

The second objective also sought to examine the impacts of carbon capping policy on output and consumer welfare. Unlike carbon tax, carbon capping which is quantity restriction on the amount of carbon emissions permissible under tightening emissions caps, the impacts quite differed from the alternative tax policy. The third and final objective analysed the effects of renewable energy feed-in-tariffs (REFITs) as a financing tool for solar PV penetration in domestic electricity supply on revenue generation and income distribution.

The study opens with an overview of the energy transition in the global electricity sector. The electricity sector together with heating the sector accounts for nearly half of the changes in anthropogenic emissions, that is, around 7 billion tons of carbon dioxide equivalent (CO2eq) added to the global stock of emissions, over the recent three decades. So, the transition requires increasing significant shares of low-carbon electricity technologies in the supply mix and ultimately phaseout fossil-fuel technologies to augment the global emissions mitigation struggle to keeping global temperatures well below $2^{o}C$ compared to pre-industrial levels.

For this purpose, it was argued that apart from opening up clear possibilities to solve global climate challenges, energy transition could offer immediate economic opportunities in green jobs, electricity output, and the potential for a long-term decline in energy costs that would help solve many other resource issues and lead to a palpably more prosperous global economy (Krishnan et al., 2022). Notwithstanding this potential for growth, the net-zero transition is also significantly front-loaded, with varying effects among sectors, communities, countries and regions, much of which depends on how the transition is managed. Presently, the transition comes at the time where scores of African countries suffer from insufficient electricity generation capacity and access rates.

The research problem is that, despite the broad spectrum of literature on net-zero transition and rapid decarbonisation of the electricity market, literature is still non-exhaustive in accounting for feedback impacts across all sectors of a national economy due to carbon abatement policies in developing countries. Failure to account for feedback impacts in transition policies results in biases in cost and benefits of net-zero transition, at least in the short-to-medium term. This study sought to fill this gap in the extant literature by computing the economic effects of energy transition in the electricity sector of Ghana through computable general equilibrium (CGE) and microsimulation models.

The CGE approach, opposed to a single sector, partial equilibrium assessment of a country, offered gainful ex-ante insights into diverse effects on each institution for each transition policy implemented. It was formulated and subsequently analysed three alternate transition policies for the three (3) net-zero policy options: (i) carbon taxation, (ii) carbon capping, and (iii) feed-in-tariff renewables. For all three, it was postulated that faster penetration of the transition interventions will adversely impact economic growth and welfare.

This research is timely as developing countries, especially those in Africa, seek rapid growth and economic recovery from further devastations caused by COVID-19 pandemic and the Russian-Ukraine war since 2020 and still pushing through the net-zero energy transition by ramping up efforts enshrined in the NDCs. By unravelling the economic implications in relation to the transition, adequate policy measures including energy efficiency in power generation and effective renewable energy financing would be addressed going forward. The study is therefore relevant for underdeveloped electricity markets seeking to accelerate efforts towards net-zero transition by 2030, taking cognisance of the underlying economic implications of rate of acceleration on growth and welfare.

This study was based on the positivists' philosophy of research. Flowing from this philosophy, is the quantitative paradigm that uses quantitative research methods and data to study about a phenomenon. This was applied to study the behaviour of rational economic agents to climate-mitigation policies in the electricity industry and the associated full-equilibrium impacts across all markets in the domestic economy in a CGE and microsimulation frameworks. In the general equilibrium framework, all economic agents optimize their objective functions and are in equilibrium (Debreu, 1982). In essence, in the CGE, all economic agents in a domestic economy optimise their supply and demand choices in response to a policy shock in the electricity sector. For the first and second objectives were analysed using a computable general equilibrium (CGE) framework whereas a financial microsimulation is used for the third and final objective.

Analysis of emissions reduction based on general equilibrium framework is able to examine the impacts of broad policy changes and macro shocks on all sectors, markets and economic players. CGE models specify all their economic relationships to predict the change in policy variables and measure the economic impacts at a given level of technology and consumer preferences. The agents and markets interact iteratively to achieve an equilibrium in prices for all markets in an economy. The model mathematically represents relevant behaviour of key economic agents in a small open economy, and how they interact to achieve equilibrium. The economic agents are typically producers, consumers, government, private investment activities, and rest of the world.

First, the study adopted a relatively broad and nested production technology, KLEMS (Capital (K), Labour (L), Energy E, physical Material inputs (M), and Services inputs (S)), used in the production of most economic goods and services. The permutation of substitutions in the nested function is KE-L-MS where capital and energy are first combined by a Leontief production technology into a composite input (KE). The composite input KE is in turn combined with labour (L) and aggregate intermediate inputs (MS) using a CES technology. Individual intermediate inputs from domestic and import sources are, nonetheless, transformed into aggregate inputs using a Leontief production technology.

Model closures applied to the two CGE models were justifiably the closest to the workings of the Ghanaian economy. First among them is the savings-investment closure. In this closure, investment is savings driven. This means, investment is treated as exogenous. Thus, upon an imposition of emissions cap and tax, household savings is expected to endogenously change to equilibrate the S-I balance.

Secondly, the exchange rate is assumed to be flexible while foreign savings are fixed. For the current account, it is assumed that a flexible exchange rate adjusts in order to maintain a fixed level of foreign borrowing (or negative savings). In other words, the external balance is held fixed in foreign currency. This closure is appropriate given Ghana’s commitment to a flexible exchange rate system, and the belief that foreign borrowing is not inexhaustible.

Thirdly, Government savings are also assumed flexible whereas direct tax rate is fixed. In the government account the level of direct and indirect tax rates, as well as real government consumption, are held constant. As such the balance on the government budget is assumed to adjust to ensure that public expenditures equal receipts. This closure is chosen since it is assumed that changes in direct and indirect tax rates are politically motivated and thus are adopted in isolation of changes in other policies or the economic environment. Finally, consumer price index (CPI) is assumed to be fixed and chosen as the numeraire while domestic producer price (DPI) is assumed flexible.

The experiments conducted using the CGE framework were teased out of key strategies outlined in Ghana's NDCs for the power sector that deal specifically with direct cuts in carbon emissions. In the updated GH-NDCs, Ghana's business-as-usual (BAU) emissions are expected to increase from 43.02 MtCO2e in 2016 to 73.3 MtCO2e in 2030. The study christened an unconditional 15 percent, 45 percent and 95 percent lower-than-BAU emissions by 2030 as 'Tortoise', 'Horse' and 'Cheetah' scenarios, respectively. The core of the CGE model is the standard model by the International Food Policy Research Institute (IFPRI) (Robinson & Lofgren, 2005). However, the standard IFPRI model is tweaked to grossly suit the analysis set out in this study. This included a modification to accommodate an imperfect market under an emissions capping policy.

The CGE models were calibrated with the 2015 Social Accounting Matrix (SAM). Production, trade, and consumption elasticities are adopted from GTAP 8 database (Aguiar et al., 2016), and from comparable developing countries like Kenya and Bangladesh. The SAM data is aggregated to 11 products and sectors with a split of the electricity sector into hydro, thermal and solar electricity. Also, agriculture products are aggregated into food, export, and other agricultural commodities. Further, to identify the impacts of carbon tax on production of electricity, fuel (petroleum) is modelled as a factor input in electricity generation other than an intermediate input. This is particularly to address factor substitution between fuel and capital inputs.

On the other hand, the financial microsimulation analysis conducted on REFITs in Ghana's case was implemented using the SUBSIM tool in STATA 17. The sixth and seventh rounds of the Ghana Living Standard Surveys collected in 2012/2013 and 2016/17, respectively. However, annual GDP per capita growth, consumer price index (CPI) and population estimates from World Development Indicator (WDI) while retail electricity prices were from Ghana's electricity retailer (Electricity Company of Ghana's (ECG) 2016 tariff reckoner), and the 2013 and 2016 REFITs from Ghana's Public Utility Regulatory Commission (PURC).

On the impact of carbon tax on the electricity sector, the study found that the rise in production cost forces producers to internalise the cost of carbon pollution from the upstream. Domestic electricity supply compared to the baseline year increases by almost 4 percent in the Tortoise scenario with a cedi equivalent tax rate of US$ 0.006/MtCO2e of gross output, while the reverse is true for a higher cedi equivalent tax rate of US$ 0.039/ MtCO2e in the Cheetah scenario. A spillover-effect from thermal electricity generation to hydroelectricity and solar PV was also present through multiple price-rebound-effects in domestic goods and services.

Generally, a moderate tax rate (Horse scenario) to a minimal tax rate (Tortoise scenario) still generates higher outputs over the base year. On the other hand, final demand price of thermal electricity exceptionally increased in the Tortoise scenario. It is a known fact that a new production tax increases industry marginal cost, and as the result industry price also increases. This directly increases industry supply coupled with the shift in hydroelectricity to thermal and solar. Also, government savings become negative, driven by increasing government expenditure. Generally, when government expenditure increases, its savings goes negative, and vice versa. The Tortoise scenario presents the worst fiscal balance on government's books, and even though revenue from carbon taxes increases astronomically, hike in government expenditure overturns the gains in revenue.

As regards economic growth, a minimal carbon tax rate still induces about 32 percent growth compared to the baseline. Notwithstanding, exports decline. The electricity sectors in particular recorded higher nominal growth compared to the baseline in only the Tortoise case but in real terms, there were marginal increases over the baseline unlike the highest carbon tax rate scenario which yields a negative real growth compared with the baseline.

Finally, it was showed that rapid tax rates have rather lower welfare burdens on consumers possibly through linkages effects from increased government expenditure. It could be explained as taxes raised are compensated through increased government expenditure to support private consumption and investment given the base-year's expenditure shares of the government and no endogenous change of its spending lifestyle. Hence, welfare burden drops between the BAU case of no carbon tax to a minimum tax in the Tortoise scenario. The urban non-poor have the highest welfare burden followed by the rural poor.

Moving on to the second objective regarding emissions capping, the policy decreased outputs and induced ripple effects in alternate generation technologies. The spillover effect on hydroelectricity and on solar generation are largely positive. Thus, greener technologies step up production to fill in the loss in thermal production. However, it is conspicuous that clean electricity cannot sufficiently replace the shortfall in thermal generation considering the gap in thermal generation between BAU and the higher policy scenarios. On a whole, outputs from cleaner technologies, namely hydroelectricity and solar PV, rise above baseline levels when carbon capping is introduced on thermal electricity generation.

Moreover, as thermal generation is curtailed through emissions capping, electricity imports from neighbouring countries to augment the shortfall after hydroelectricity and solar PV generation have ramped up production become necessary. This reflects the large contribution of thermal electricity to Ghana’s electricity needs with diminishing shares of hydro and solar. Generally, the Ghana’s import bill for electricity would rise with tighter caps on carbon emissions. Talking about rising import bills due to emissions capping, government savings consequently decline monotonically from the BAU to the tightest cap in the Cheetah scenario. Revenue outperforms expenditure only up to a minimal cap in the Tortoise Scenario, but beyond that government expenditure outweighs revenue leading to negative government savings.

Additionally, the final demand price of thermal electricity increases significantly with tighter caps in the Horse and Cheetah scenarios. That is, producers will pass on the scarcity price necessitated by caps on emissions through the market price. This is unlike the BAU and the milder-cap case where producers absolve the rise in cost of production by caps on emissions. Also, the weighted average price of electricity by technologies is expected to increase with higher caps on thermal generation. The rising price of electricity is from declining thermal electricity supply over the base-year, limited uptake in alternative technologies, and a rise in imports.

The study found, also, that a carbon capping policy will cut more than 2 percent in growth, even with a minimal cap rate, and nearly 3 percent of economic growth forfeited for a tighter cap as in the case of the Cheetah Scenario. Within the energy sector, renewable technologies in the form of hydroelectricity and solar PV experienced significant real growth. In terms of growth distribution, the urban non-poor households were the least affected, possibly, due to smaller share of electricity consumption compared to other households.

Also, apart from the BAU case, rural households have higher changes in welfare than the urban households, except for the urban poor. More broadly, tighter carbon caps induced higher welfare changes for consumers. This is unlike carbon taxes that could generate revenue to cushion aggregate demand and support households, emissions capping has no such fiscally neutral arm. Hence, welfare burden increases for the most vulnerable, especially the urban poor who is without fiscal support.

Finally, the results of the microsimulation exercise examining the impacts of REFITs in the residential demand sector on government revenue as well as consumer welfare showed that higher solar PV penetration rate corresponds to higher revenue for REFITs. Marginal revenue from REFITs peaks around GHS 40,000 in 2013. This doubles in about a decade after to around GHS80,000 by 2021 in nominal terms. By 2030, the revenue threshold hits about GHS 1.5million. A greater portion of the total revenue is realised after 2021. While the revenue impact thresholds increased, the optimal change in price (shown with the red line) decreased as we moved from 2013 to 2030, from about 40 percent in 2013 to about 10 percent in 2030. This was orchestrated by increased rate of penetration of solar generation and increased demand for electricity by residential consumers.

On the other hand, distributional impacts on consumer welfare through increases in energy prices showed that, apart from the top quintile group (Q5), REFITs generally had an adverse, downward sloping impact on welfare of residential consumers. The outlier Q5 consumers were not negatively affected attributably because their expenditure share of electricity consumption is smallest compared to other household groups. This indicates that REFITs would be less harmful to consumer welfare during times of higher economic growth where consumers have higher incomes. Other than that, to mitigate the impacts of REFITs on consumers, the government ought to make fiscally neutral transfers to supports vulnerable households.

In this work, it has been demonstrated that the level of transfer required to ease the adverse distributional impacts of price increases on consumer welfare. Due to inequalities in incomes, a cedi transfer to all households will have varying welfare impacts on different households. Households in higher quintiles benefit from transfers if the level of transfer as a percentage of the price change is substantial.

Last but equally important, the study discussed the opportunity cost of no policy action regarding renewable energy production up to 2030. This is intended to quantify what the country Ghana misses if there were no REFIT to fund renewable energy generation nor any alternative that achieves same. This is particularly relevant in guiding policy dialogue whenever there is a proposal to scrap REFITs. Now, Ghana has reformed its REFITs in its amended Renewable Energy Act 2020 and seeks to replace REFITS with competitive procurement processes through tendering and auctions. Yet, there is general lack of institutional structures and measures that would facilitate a more transparent and competitive bidding process.

Hence, the quantification of what the country stands to forfeits in the interim in terms of MW of electricity and carbon savings if no alternative policy fails to kick off before 2030. By the results obtained, Ghana stands to forfeit up to 6.33MW of solar electricity and 0.27 metric tons of carbons savings if no renewables were not introduced from until 2030. Between 2021 to 2030 alone, a total of 5.1WM of solar electricity and 0.21MtCO2 of carbon savings would be forfeited after scraping REFITs without an alternative renewable energy investment in place by 2030.

Conclusion

In the first place, the author begins by restating the aim of the study set out in the beginning. That is, to analyse the economic impacts of a domestic African economy to net-zero transition pathways in the electricity sector in the medium term, using Ghana as a case country. So, based on the research questions, analysis and the discussions thus far, the author asserts the following conclusions.

First and foremost, it has been established that carbon tax reduces thermal electricity output and decreases economic welfare of consumers. Nonetheless, by recycling the tax revenue to support vulnerable households, the magnitude of impact is reduced. This is an indication that curbing carbon emissions through taxes on thermal electricity in Ghana will not be neutral on growth and welfare unless accompanied by adequate transfers to vulnerable households to compensate for welfare losses.

The second conclusion arising out of the study is that carbon capping reduces electricity outputs and decreases economic welfare more than a comparable carbon tax policy. This specially draws a line of distinction in terms of economic growth and welfare relative to the impacts of carbon tax versus carbon capping policies as has been demonstrated that carbon taxation has less adverse impacts than any level of cap restrictions. Lastly, it has been proven that REFITs negatively affect welfare as the rate of solar PV penetration rises.

Hence, in a nutshell, by this study it has been shown that accelerated deployment of carbon taxes, carbon capping and REFITs to promote rapid carbon mitigation in the electricity sector have adverse impacts on economic growth, electricity supply and consumer welfare. In relative sense, however, carbon taxation has less adverse impact on welfare than carbon capping through re-distribution of tax revenue. REFITs, on the other hand, makes available substantial revenue to fund renewable electricity production though accompanied by higher consumer welfare losses as REFITs also increase.

Policy Implications

The foregoing conclusions are necessary to guide carbon mitigation policies towards decarbonisation of Ghana's electricity sector. Most significantly, the nuanced analysis provided in this study and the conclusions thereof could be useful to policy makers and economic regulators of the sector like the Energy Commission and the Public Utility Regulatory Commission (PURC) towards the implementation of the country's updated nationally determined contributions in the electricity sector. This research is timely as Ghana also seeks economic recovery from the devastations caused by COVID-19 pandemic, the Russian-Ukraine war since 2020, and the fiscal challenges thereafter and still pushing through the energy transition by ramping up efforts enshrined in the GH-NDCs. By unravelling the underlying economic implications in relation to decarbonisation agenda in the electricity sector, this study provides strong evidence of strategic options the country could afford in charting a path forward.

Carbon taxation: Regarding carbon taxes, this study found that carbon tax at much higher levels will reduce output from thermal electricity and support renewable electricity by 2030. Hence, any attempt to introduce carbon tax to curtail emissions in Ghana's electricity sector must be gradual and minimal around GHS 195/MtCO2 (Tortoise scenario). This guarantees a real fine balance between growth and curtailment in thermal generation. If not, any higher rate will have steeper decline in real growth and higher consumer welfare loses for the most vulnerable residential consumers of electricity.

Carbon capping: Here, the study has also documented evidence of impacts from graduated levels of carbon caps. Compared to carbon taxes, higher caps will be more effective in decreasing production from fossil-fuel-based technologies (i.e., thermal electricity) and, at the same, time increasing production from greener technologies like hydro and solar electricity by 2030. However, steeper caps yield worse economic growth and raise higher welfare burdens on the poor, especially in the urban centres and the rural poor than carbon taxes. Because caps alone do not generate commiserate revenue, government savings is adversely affected due to decreases in final goods and services in the national economy. Hence, if the goal is to achieve drastic decline in thermal electricity, then carbon capping is most effective than taxes but has more adverse effects on economic growth and welfare than carbon taxes.

Renewable energy feed-in-tariff: Finally, this study brought to the fore that higher solar PV penetration rate corresponds to higher revenue for REFITs. This is due to expected rapid growth, coupled with higher penetration rate of solar PV over the next decade. However, REFITs have an adverse, downward sloping impact on welfare of residential consumers. On the other hand, Ghana stands to forfeit up to 6.33MW of solar electricity and 0.27 metric tons of carbons savings if no renewables were not introduced from 2013 to 2030. This needs prompt attention of policy makers to quickly resolve the policy vacuum created after abolishing REFITs and instituting competitive procurement regime, whose guidelines have not been developed yet.

Contributions to Knowledge

The author has shown the gaps in the existing body of research that have mostly failed to assess the economy-wide medium-to-long term economic costs of transition policies in Ghana’s electricity market. Generally, lack of full assessment and incorporation of the cost of transition in the nationally determined contributions have often resulted in transition inertia in most developing countries. Thus, the aim of this study has been to assess the economic impacts of transition scenarios in a developing electricity sector using Ghana's NDCs and the electricity sector for this purpose. The novel approach and its findings obtained in the study are key in guiding the rapidity and policy options of energy transition in Ghana's electricity sector by 2030.

Specifically, the study has successfully modelled an economy-wide assessment of hypothetical cases of carbon tax and carbon cap policies using a CGE framework calibrated to Ghana's economy. These policies, which have not been modelled for Ghana in the literature in a manner as was done in this study, were thought of as policy channels through which Ghana achieves its emissions targets stated in the GH-NDCs by 2030. Most of Ghana's policy planning and analysis underlying policy documents like the GH-NDCs have depended on bottom-up analytical toolkits that provide greater detail of the electricity ecosystem but fail to account for the optimal behaviour of economic agents. Thus, transition planning has often not been accompanied with full economic impacts of scenarios and policy choices.

Hence, this study has shown that, first, adoption of carbon tax would be superior to an alternative carbon cap policy in terms of both gross output and welfare impacts. Secondly, in each of the policy alternatives, a slow penetration rates will yield optimal balance between output growth and consumer welfare. These are as result of accounting for the full effects of emissions abatement policies emanating both from within and outside the electricity sector.

Most importantly, results of the novel microsimulation of REFITs in Ghana's residential sector has also generated insightful perspectives into renewable energy finance through feed-in-tariff, which are not elsewhere determined. The micro analysis of REFITs has showed how much megawatts of electricity Ghana would have gained in it had sustained its REFITs by 2030, including the resultant tax revenue and consumer welfare losses. In this regard, the study shows that sustaining REFITs policies till 2030 would not be welfare-maximizing if they are without sufficient government transfer to vulnerable households.

Limitations of the Study

The first major challenge with CGE models is the assumption of perfect foreknowledge of economic agents, so that there is no room for deviations from optimal behaviour. In other words, CGE models do not include stochastic terms that measure deviations of model estimates from observed values as pertains in econometric models. Thus, it precludes CGE models from being ideal for forecasting based baseline economic values. It is important, therefore, that one interprets results of simulations from a CGE model as ex-ante '*What-if Analysis*' but not as being predictive of the future. Hence, the results of this study are interpreted as not being a forecast of Ghana's future in 2030.

Related to the above, a static CGE model, as used in this study, becomes simply relevant to analyse alternative scenarios when the fundamental structure of the economy is assumed constant between two static years. The base year economy is built on detailed economic exchanges in the Social Accounting Matrix (SAM) for Ghana in 2015. Therefore, by assuming an insignificant change in the structure of the Ghanaian economy between the base year 2015 and 2030, one can then assess impact of alternative policy shocks between the two static years. This assumption also underpins the microsimulation of REFITs on the residential demand sector. However, the results could be challenged if the economy evolves significantly over the decade and half. Nonetheless, given that the structure of the Ghanaian economy has barely changed for the past several decades after its structural adjustment programme in the early 1990s, it is not out of place to safely assume that the economic fundamentals will be the same by 2030.

Third and lastly, agents' behavioural parameters in the form of elasticities of substitution were not empirically validated using data of the Ghanaian economy but were obtained from estimates in comparable developing countries like Kenya and elsewhere. This is due to lack of empirical data like price and quantities of factor inputs, and final goods and services necessary for empirical estimation of demand elasticities of both factors of production and final goods and services. The challenge with borrowing elasticity estimates from other jurisdiction is obvious – no two countries are equal. Despite this, demand elasticities are relatively stable and consistent among countries of comparable economic structure (Hutchings et al., 2022). This allows a fair translation of economic agents' demand elasticities into another jurisdiction that lacks empirical data for estimation as was done in this study.

Suggestions for Further Research

This study was conducted under a set of neoclassical assumptions. Although these assumptions, in the author's opinion, sufficiently mirror the workings of the Ghanaian economy and the electricity sector, future studies can investigate using:

i. Endogenous growth modelling approach, a post-neoclassical theory of endogenous technical innovation in contrast to the autonomous technical progress used in this study

ii. Similarly, if one is interested in knowing the changes in simulated impacts in-between-years rather than two static years, then a recursive dynamic CGE modelling is ideal. In this study, the between years changes were of no particular importance as the aim was to access the static state of affairs by the end of 2030.

iii. Much technological details of the electricity sector are always missing in macroeconomic analysis. Therefore, an integrated modelling approach could be used to link the macro model with a bottom-up models with high resolution of technologies in the electricity value chain if one is interested to understand with greater technical details of the electricity sector.

REFERENCES

Abel, A. B., Dixit, A. K., Eberly, J. C., & Pindyck, R. S. (1996). Options, the value of capital, and investment. *The Quarterly Journal of Economics, 111*(3), 753–777.

Abel, A. B., & Eberly, J. C. (1994). A Unified Model of Investment Under Uncertainty. *The American Economic Review*, *84*(5), 1369–1384.

Abel, A. B., & Eberly, J. C. (1996). Optimal investment with costly reversibility. *The Review of Economic Studies*, *63*(4), 581–593.

Abel, A. B., & Eberly, J. C. (1999). The effects of irreversibility and uncertainty on capital accumulation. *Journal of Monetary Economics*, *44*(3), 339–377.

Acheampong, T., Menyeh, B. O., & Agbevivi, D. E. (2021). Ghana's changing electricity supply mix and tariff pricing regime: Implications for the energy trilemma. *Oil, Gas and Energy Law*, *19*(3). URL: www.ogel.org/article.asp?key=3974

Ackah, I., & Graham, E. (2021). Meeting the targets of the Paris Agreement: An analysis of renewable energy (RE) governance systems in West Africa (WA). *Clean Technologies and Environmental Policy*, *23*, 501–507.

Ahiataku-Togobo, W. (2016). *Five Years of Implementing the Renewable Energy Law Act 832 – Successes and Challenges*. Ghana Energy Commission. http://energycom.gov.gh/files/Five%20Years%20of%20Implementing%20the%20Renewable%20Energy%20Law%20Act%20832%20%E2%80%93%20Successes%20and%20Challenges.pdf

Alizamir, S., de Véricourt, F., & Sun, P. (2016). Efficient feed-in-tariff policies for renewable energy technologies. *Operations Research, 64*(1), 52–66.

Araar, A., Choueiri, N., & Verme, P. (2017). *The quest for subsidy reforms in Libya*. Springer. http://documents.worldbank.org/curated/en/344571467980552949/The-quest-for-subsidy-reforms-in-Libya

Araar, A., & Verme, P. (2019). *Prices and Welfare*. Springer.

Armington, P. S. (1969). *A Theory of Demand for Products Distinguished by Place of Production*.

Armstrong, A., & Hagel, J. (2009). The real value of online communities. In *Knowledge and communities* (pp. 85–95). Routledge.

Arndt, C., Davies, R., Gabriel, S., Makrelov, K., Merven, B., Hartley, F., & Thurlow, J. (2016). A sequential approach to integrated energy modeling in South Africa. *Applied Energy*, *161*, 591–599.

Arndt, C., Robinson, S., & Tarp, F. (2002). Parameter estimation for a computable general equilibrium model: A maximum entropy approach. *Economic Modelling*, *19*(3), 375–398.

Arora, N. K., Fatima, T., Mishra, I., Verma, M., Mishra, J., & Mishra, V. (2018). Environmental sustainability: Challenges and viable solutions. *Environmental Sustainability*, *1*, 309–340.

Arrow, K. J. (1974). General economic equilibrium: Purpose, analytic techniques, collective choice. *The American Economic Review*, *64*(3), 253–272.

Aslan, A., & Altinoz, B. (2021). The impact of natural resources and gross capital formation on economic growth in the context of globalization: Evidence from developing countries on the continent of Europe, Asia, Africa, and America. *Environmental Science and Pollution Research*, *28*, 33794–33805.

Aspers, P., & Beckert, J. (2011). Value in markets. *The Worth of Goods: Valuation and Pricing in the Economy*, *3*, 39.

Balk, B. M. (2021). *Productivity* (1st ed.). Springer.

Bandara, J. S. (1991). Computable general equilibrium models for development policy analysis in LDCs. *Journal of Economic Surveys*, *5*(1), 3–69.

Banerjee, A. V., & Duflo, E. (2005). Growth theory through the lens of development economics. *Handbook of Economic Growth*, *1*, 473–552.

Barzel, Y. (1982). Measurement cost and the organization of markets. *The Journal of Law and Economics*, *25*(1), 27–48.

Baumol, W. J. (1972). On taxation and the control of externalities. *The American Economic Review*, *62*(3), 307–322.

Baxter, M., & King, R. G. (1993). Fiscal policy in general equilibrium. *The American Economic Review*, 315–334.

Bergh, J. van den, & Botzen, W. (2020). Low-carbon transition is improbable without carbon pricing. *Proceedings of the National Academy of Sciences*, *117*(38), 23219–23220. https://doi.org/10.1073/pnas.2010380117

Bersalli, G., Menanteau, P., & El-Methni, J. (2020). Renewable energy policy effectiveness: A panel data analysis across Europe and Latin America. *Renewable and Sustainable Energy Reviews, 133*, 110351. https://doi. org/10.1016/j.rser.2020.110351

Bertola, G. (1988). *Adjustment costs and dynamic factor demands: Investment and employment under uncertainty* [PhD Thesis]. Massachusetts Institute of Technology.

Bertola, G., & Caballero, R. J. (1994). Irreversibility and aggregate investment. *The Review of Economic Studies*, *61*(2), 223–246.

Best, R., Burke, P. J., & Jotzo, F. (2020). Carbon Pricing Efficacy: Cross-Country Evidence. *Environmental and Resource Economics*, *77*(1), 69–94. https://doi.org/10.1007/s10640-020-00436-x

Beveridge, W. H. (2014). *Full employment in a free society (Works of William H. Beveridge): A report*. Routledge.

Bierbrauer, F., Felbermayr, G., Ockenfels, A., Schmidt, K. M., & Südekum, J. (2021). *A CO2-border adjustment mechanism as a building block of a climate club*. Kiel Policy Brief.

Böhringer, C., Cuntz, A. N., Harhoff, D., & Asane-Otoo, E. (2014). *The impacts of feed-in tariffs on innovation: Empirical evidence from Germany*.

Böhringer, C., García-Muros, X., & González-Eguino, M. (2022). Who bears the burden of greening electricity? *Energy Economics*, *105*, 105705.

Bovenberg, A. L. (1988). The corporate income tax in an intertemporal equilibrium model with imperfectly mobile capital. *International Economic Review*, 321–340.

Calderón, S., Alvarez, A. C., Loboguerrero, A. M., Arango, S., Calvin, K., Kober, T., Daenzer, K., & Fisher-Vanden, K. (2016). Achieving CO2 reductions in Colombia: Effects of carbon taxes and abatement targets. *Energy Economics*, *56*, 575–586.

Campbell, J. R. (1998). Entry, exit, embodied technology, and business cycles. *Review of Economic Dynamics*, *1*(2), 371–408.

Carley, S., Baldwin, E., MacLean, L. M., & Brass, J. N. (2017). Global expansion of renewable energy generation: An analysis of policy instruments. *Environmental and Resource Economics*, *68*, 397–440.

Cherrington, R., Goodship, V., Longfield, A., & Kirwan, K. (2013). The feed-in tariff in the UK: A case study focus on domestic photovoltaic systems. *Renewable Energy*, *50*, 421–426.

Coady, D., Jahan, S., Machado, F., & Gu, M. (2023). *The Distributional and Fiscal Implications of Public Utility Pricing*. http://dx.doi.org/10.5089/9798400245527.001

Coffman, M., Bernstein, P., Schjervheim, M. P., La Croix, S., & Hayashida, S. (2023). A comparison of state-level carbon reduction strategies: A case study of Hawaii. *Energy and Climate Change*, *4*, 100100.

Ćorović, N., Urošević, B. G., & Katić, N. (2022). Decarbonization: Challenges for the electricity market development—Serbian market case. *Energy Reports*, *8*, 2200–2209.

Costantini, V., Crespi, F., & Paglialunga, E. (2019). Capital–energy substitutability in manufacturing sectors: Methodological and policy implications. *Eurasian Business Review*, *9*, 157–182.

Couture, T., & Gagnon, Y. (2010). An analysis of feed-in tariff remuneration models: Implications for renewable energy investment. *Energy Policy*, *38*(2), 955–965.

Cova, B. (1997). Community and consumption: Towards a definition of the "linking value" of product or services. *European Journal of Marketing*, *31*(3/4), 297–316.

Cozzi, L., Gould, T., Bouckart, S., Crow, D., Kim, T., Mcglade, C., Olejarnik, P., Wanner, B., & Wetzel, D. (2020). World energy outlook 2020. *IEA: Paris, France*, *2050*, 1–461.

Creswell, J. W. (2011). Controversies in mixed methods research. *The Sage Handbook of Qualitative Research*, *4*(1), 269–284.

Creswell, J. W., & Creswell, J. D. (2018). *Research Design: Qualitative, Quantitative and Mixed Methods Approaches* (5th edition). Sage.

Creswell, J. W., & Tashakkori, A. (2007). Differing perspectives on mixed methods research. In *Journal of mixed methods research* (Vol. 1, Issue 4, pp. 303–308). Sage publications Sage CA: Los Angeles, CA.

Dasgupta, P. (2021). *The economics of biodiversity: The Dasgupta review*. Hm Treasury.

De Santis, R. A. (2002). A computable general equilibrium model for open economies with imperfect competition and product differentiation. *Journal of Economic Integration*, 311–338.

Debreu, G. (1982). Existence of competitive equilibrium. *Handbook of Mathematical Economics*, *2*, 697–743.

Decaluwé, B., & Martens, A. (1988). CGE modeling and developing economies: A concise empirical survey of 73 applications to 26 countries. *Journal of Policy Modeling*, *10*(4), 529–568.

DeGhetto, K., Gray, J. R., & Kiggundu, M. N. (2016). The African Union's Agenda 2063: Aspirations, challenges, and opportunities for management research. *Africa Journal of Management*, *2*(1), 93–116.

Del Río, P. (2012). The dynamic efficiency of feed-in tariffs: The impact of different design elements. *Energy Policy*, *41*, 139–151.

Diao, X., & Thurlow, J. (2012). A recursive dynamic computable general equilibrium model. In *Strategies and priorities for African agriculture: Economywide perspectives from country studies* (Vol. 2, pp. 17–50). Washington DC: International Food Policy Research Institute.

Dillon, B., & Barrett, C. B. (2017). Agricultural factor markets in Sub-Saharan Africa: An updated view with formal tests for market failure. *Food Policy*, *67*, 64–77.

Dissanayake, S., Mahadevan, R., & Asafu-Adjaye, J. (2020). Evaluating the efficiency of carbon emissions policies in a large emitting developing country. *Energy Policy*, *136*, 111080.

Dixit, A. (1989). Hysteresis, import penetration, and exchange rate pass-through. *The Quarterly Journal of Economics*, *104*(2), 205–228.

Dixit, A. K., & Pindyck, R. S. (1994). *Investment under uncertainty*. Princeton university press.

Dong, C., Qi, Y., Dong, W., Lu, X., Liu, T., & Qian, S. (2018). Decomposing driving factors for wind curtailment under economic new normal in China. *Applied Energy*, *217*, 178–188.

Dorband, I. I., Jakob, M., Kalkuhl, M., & Steckel, J. C. (2019). Poverty and distributional effects of carbon pricing in low- and middle-income countries – A global comparative analysis. *World Development*, *115*, 246–257. https://doi.org/10.1016/j.worlddev.2018.11.015

Dubey, P., Geanakoplos, J., & Shubik, M. (2005). Default and punishment in general equilibrium 1. *Econometrica*, *73*(1), 1–37.

Dumortier, J., & Elobeid, A. (2021). Effects of a carbon tax in the United States on agricultural markets and carbon emissions from land-use change. *Land Use Policy*, *103*, 105320.

Düppe, T., & Weintraub, E. R. (2014). *Finding equilibrium: Arrow, Debreu, McKenzie and the problem of scientific credit*. Princeton University Press.

EPA. (2019). *Ghana's Fourth National Greenhouse Gas Inventory*. Environmental Protection Agency.

EPA. (2022). *Ghana's Fifth National Greenhouse Gas Inventory*. Environmental Protection Agency.

Fagiolo, G., Guerini, M., Lamperti, F., Moneta, A., & Roventini, A. (2019). Validation of agent-based models in economics and finance. *Computer Simulation Validation: Fundamental Concepts, Methodological Frameworks, and Philosophical Perspectives*, 763–787.

Falcone, P. M. (2020). Environmental regulation and green investments: The role of green finance. *International Journal of Green Economics*, *14*(2), 159–173.

Felipe, J., & Fisher, F. M. (2006). Aggregate production functions, neoclassical growth models and the aggregation problem. *Estudios de Economía Aplicada*, *24*(1), 127–163.

Finon, D. (2019). Carbon policy in developing countries: Giving priority to non-price instruments. *Energy Policy*, *132*, 38–43.

Fosu, A., & Aryeetey, E. (2008). Ghana's post-independence economic growth. *The Economy of Ghana: Analytical Perspectives on Stability, Growth, and Poverty*. *Oxford: James Currey*, 36–77.

Franks, M., Lessmann, K., Jakob, M., Steckel, J. C., & Edenhofer, O. (2018). Mobilizing domestic resources for the Agenda 2030 via carbon pricing. *Nature Sustainability*, *1*(7), 350–357. https://doi.org/10.1038/s41893-018-0083-3

Fremstad, A., & Paul, M. (2019). The impact of a carbon tax on inequality. *Ecological Economics*, *163*, 88–97.

Geanakoplos, J. (1989). Arrow-Debreu model of general equilibrium. In *General Equilibrium* (pp. 43–61). Springer.

Gerbeti, A. (2021). Market mechanisms for reducing emissions and the introduction of a flexible consumption tax. *Global Journal of Flexible Systems Management*, *22*(Suppl 2), 161–178.

Ghana Energy Commission. (2019). Ghana Renewable Energy Master Plan. *Renewable-Energy-Masterplan-February-2019. Pdf*. https://www.energycom.gov.gh/files/Renewable-Energy-Masterplan-February-2019.pdf

Ghana Energy Commission. (2022). *Energy Statistics*. Ghana Energy Commission.

Górnowicz, R., & Castro, R. (2020). Optimal design and economic analysis of a PV system operating under Net Metering or Feed-In-Tariff support mechanisms: A case study in Poland. *Sustainable Energy Technologies and Assessments*, *42*, 100863.

Grösche, P., & Schröder, C. (2014). On the redistributive effects of Germany's feed-in tariff. *Empirical Economics*, *46*, 1339–1383.

Grubb, M., & Neuhoff, K. (2006). Allocation and competitiveness in the EU emissions trading scheme: Policy overview. *Climate Policy*, *6*(1), 7–30.

GSS, ISSER, & IFPRI. (2017). *Report on the 2015 Social Accounting Matrix (SAM) for Ghan*.

Hahn, F. (1980). General equilibrium theory. *The Public Interest*, 123.

Haites, E. (2018). Carbon taxes and greenhouse gas emissions trading systems: What have we learned? *Climate Policy*, *18*(8), 955–966.

Harris, R. (1984). Applied general equilibrium analysis of small open economies with scale economies and imperfect competition. *The American Economic Review*, *74*(5), 1016–1032.

Helpman, E. (1981). International trade in the presence of product differentiation, economies of scale and monopolistic competition: A Chamberlin-Heckscher-Ohlin approach. *Journal of International Economics*, *11*(3), 305–340.

Henningsen, A., Henningsen, G., & van der Werf, E. (2019). Capital-labour-energy substitution in a nested CES framework: A replication and update of Kemfert (1998). *Energy Economics*, *82*, 16–25.

Hillberry, R., & Hummels, D. (2013). Trade elasticity parameters for a computable general equilibrium model. In *Handbook of computable general equilibrium modeling* (Vol. 1, pp. 1213–1269). Elsevier.

Hitaj, C., & Löschel, A. (2019). The impact of a feed-in tariff on wind power development in Germany. *Resource and Energy Economics*, *57*, 18–35.

Hlovor, I. K. (2023). The 'Second U-Turn': Domestic Politics and Foreign Economic Policy Choice in Ghana. *The African Review*, *1*(aop), 1–43.

House-Peters, L. A., & Chang, H. (2011). Urban water demand modeling: Review of concepts, methods, and organizing principles. *Water Resources Research*, *47*(5).

Hudea, O. S. (2015). Classical, neoclassical and new classical theories and their impact on macroeconomic modelling. *Procedia Economics and Finance*, *23*, 309–312.

Hunt, S. D. (2007). Economic growth: Should policy focus on investment or dynamic competition? *European Business Review*, *19*(4), 274–291.

Hutchings, P., Willcock, S., Lynch, K., Bundhoo, D., Brewer, T., Cooper, S., Keech, D., Mekala, S., Mishra, P. P., Parker, A., & others. (2022). Understanding rural–urban transitions in the Global South through peri-urban turbulence. *Nature Sustainability*, *5*(11), 924–930.

IEA. (2022). *Africa Energy Outlook*. IEA. IEA (2022https://www.iea.org/reports/africa-energy-outlook-2022

International Renewable Energy Agency. (2022). *RENEWABLE CAPACITY STATISTICS 2022*. www.irena.org

IRENA, A. (2022). Renewable Energy market analysis: Africa and its regions. *International Renewable Energy Agency and African Development Bank, Abu Dhabi and Abidjan*.

Jakob, M., Chen, C., Fuss, S., Marxen, A., Rao, N. D., & Edenhofer, O. (2016). Carbon Pricing Revenues Could Close Infrastructure Access Gaps. *World Development*, *84*, 254–265. https://doi.org/10. 1016/j.worlddev. 2016.03.001

Jedwab, R., & Osei, R. D. (2012). Structural change in Ghana 1960-2010. *Institute for International Economic Policy Working Paper*.

Jenkins, J. D. (2014). Political economy constraints on carbon pricing policies: What are the implications for economic efficiency, environmental efficacy, and climate policy design? *Energy Policy*, *69*, 467–477. https://doi.org/10.1016/j.enpol.2014.02.003

Jones, R. W. (1965). The structure of simple general equilibrium models. *Journal of Political Economy*, *73*(6), 557–572.

Känzig, D. R. (2023). *The unequal economic consequences of carbon pricing*. National Bureau of Economic Research.

Keen, S., Ayres, R. U., & Standish, R. (2019). A Note on the Role of Energy in Production. *Ecological Economics*, *157*, 40–46.

Kerlinger, F. N. (1986). *Foundations of Behavioral Research* (3rd edition). Holt, Rinehart and Winston.

Khan, M. A., Khan, M. Z., Zaman, K., & Naz, L. (2014). Global estimates of energy consumption and greenhouse gas emissions. *Renewable and Sustainable Energy Reviews*, *29*, 336–344.

Khan, S. N. (2014). Qualitative research method: Grounded theory. *International Journal of Business and Management*, *9*(11), 224–233.

Kilkenny, M., & Robinson, S. (1990). Computable general equilibrium analysis of agricultural liberalization: Factor mobility and macro closure. *Journal of Policy Modeling*, *12*(3), 527–556.

Köppl, A., & Schratzenstaller, M. (2023). Carbon taxation: A review of the empirical literature. *Journal of Economic Surveys*, *37*(4), 1353–1388.

Krishnan, M., Samandari, H., Woetzel, J., Smit, S., Pacthod, D., Pinner, D., Nauclér, T., Tai, H., Farr, A., Wu, W., & others. (2022). *The net-zero transition: What it would cost, what it could bring*.

Kumar, R. (2011). *Research methodology: A step-by-step guide for beginners*. Sage.

Kwakwa, P. A. (2021). The carbon dioxide emissions effect of income growth, electricity consumption and electricity power crisis. *Management of Environmental Quality: An International Journal*, *32*(3), 470–487.

Kydland, F. E., & Prescott, E. C. (1996). The computational experiment: An econometric tool. *Journal of Economic Perspectives*, *10*(1), 69–85.

Lagac, J. M., & T Yap, J. (2020). *Evaluating the feed-in tariff policy in the Philippines*.

Lagomarsino, E. (2020). Estimating elasticities of substitution with nested CES production functions: Where do we stand? *Energy Economics*, *88*, 104752.

Lange, O. (1945). *Price flexibility and employment*. Principia Press of Trinity University San Antonio.

Levi, S., Flachsland, C., & Jakob, M. (2020). Political economy determinants of carbon pricing. *Global Environmental Politics*, *20*(2), 128–156.

Lim, B., Hong, K., Yoon, J., Chang, J.-I., & Cheong, I. (2021). Pitfalls of the EU's carbon border adjustment mechanism. *Energies*, *14*(21), 7303.

Lofgren, H., Harris, R. L., & Robinson, S. (2002). *A standard computable general equilibrium (CGE) model in GAMS* (Vol. 5). Intl Food Policy Res Inst.

Luo, G., Dan, E., Zhang, X., & Guo, Y. (2018). Why the wind curtailment of northwest China remains high. *Sustainability*, *10*(2), 570.

Madill, A., & Gough, B. (2016). *Qualitative research and its place in psychological science.*

Malerba, D., Gaentzsch, A., & Ward, H. (2021). Mitigating poverty: The patterns of multiple carbon tax and recycling regimes for Peru. *Energy Policy*, *149*, 111961.

Maxwell, J. A. (2016). Expanding the history and range of mixed methods research. *Journal of Mixed Methods Research*, *10*(1), 12–27.

McAfee, R. P., & McMillan, J. (1987). Auctions and bidding. *Journal of Economic Literature*, *25*(2), 699–738.

Mendonça, M. (2012). *Feed-in tariffs: Accelerating the deployment of renewable energy*. Routledge.

MESTI. (2021). *Ghana: Updated Nationally Determined Contribution under the Paris Agreement (2020 – 2030)*. Environmental Protection Agency, Ministry of Environment, Science, Technology and Innovation.

Meyer-Renschhausen, M. (2013). Evaluation of feed-in tariff-schemes in African countries. *Journal of Energy in Southern Africa*, *24*(1), 00–00.

Mier, M., Siala, K., Govorukha, K., & Mayer, P. (2023). Collaboration, decarbonization, and distributional effects. *Applied Energy*, *341*, 121050.

Mills, A. D., Millstein, D., Wiser, R. H., Seel, J., Carvallo, J. P., Jeong, S., & Gorman, W. (2019). *Impact of Wind, Solar, and other factors on wholesale power prices: An historical analysis—2008 through 2017*.

Ministry of Energy. (2022). *National Energy Transition Framework of Ghana*.

Ministry of Power. (2015). *National Renewable Energy Action Plan*. Ministry of Power.

Moz-Christofoletti, M. A., & Pereda, P. C. (2021). Winners and losers: The distributional impacts of a carbon tax in Brazil. *Ecological Economics*, *183*, 106945.

Nelson, R. R., & Winter, S. G. (1974). Neoclassical vs. Evolutionary theories of economic growth: Critique and prospectus. *The Economic Journal*, *84*(336), 886–905.

Nordhaus, W. D. (2021). *The spirit of green: The economics of collisions and contagions in a crowded world*. Princeton University Press.

Novshek, W., & Sonnenschein, H. (1987). General equilibrium with free entry: A synthetic approach to the theory of perfect competition. *Journal of Economic Literature*, *25*(3), 1281–1306.

Ntim, E. O., & Botchway, T. P. (2023). Ghana Beyond Aid: A Bargaining Chip for Draconian Economic Policies in Ghana. *The African Review*, *1*(aop), 1–33.

Okyere, I., & Jilu, L. (2020). The impact of export and import to economic growth of Ghana. *European Journal of Business and Management*, *12*(21), 130–138.

O'Mahony, M., & Timmer, M. P. (2009). Output, input and productivity measures at the industry level: The EU KLEMS database. *The Economic Journal*, *119*(538), F374–F403.

Partnership for Market Readiness. (2017). *Carbon tax guide: A handbook for policy makers*. World Bank.

Patt, A., & Lilliestam, J. (2018). The Case against Carbon Prices. *Joule*, *2*(12), 2494–2498. https://doi.org/10.1016/j.joule.2018.11.018

Petri, F. (2004). *General equilibrium, capital and macroeconomics: A key to recent controversies in equilibrium theory*. Edward Elgar Publishing.

Pindyck, R. S. (1982). Adjustment costs, uncertainty, and the behavior of the firm. *The American Economic Review*, *72*(3), 415–427.

Public Utilities Regulatory Commission (PURC). (2013). *Publication of Feed-in-tariffs for electricity generated from renewable sources*. Public Utilities Regulatory Commission, Ghana. https://www.purc.com.gh/attachment/873945-20210309110350.pdf

Quitzow, R., Bersalli, G., Eicke, L., Jahn, J., Lilliestam, J., Lira, F., Marian, A., Süsser, D., Thapar, S., Weko, S., & others. (2021). The COVID-19 crisis deepens the gulf between leaders and laggards in the global energy transition. *Energy Research & Social Science*, *74*, 101981.

Ramalho, R., Adams, P., Huggard, P., Hoare, K., & others. (2015). Literature review and constructivist grounded theory methodology. *Forum: Qualitative Social Research*, *16*(3), 1–13.

Ramli, M. A., & Twaha, S. (2015). Analysis of renewable energy feed-in tariffs in selected regions of the globe: Lessons for Saudi Arabia. *Renewable and Sustainable Energy Reviews*, *45*, 649–661.

Rattsø, J. (1982). Different macroclosures of the original Johansen model and their impact on policy evaluation. *Journal of Policy Modeling*, *4*(1), 85–97.

Reaños, M. A. T., & Lynch, M. Á. (2022). Measuring carbon tax incidence using a fully flexible demand system. Vertical and horizontal effects using Irish data. *Energy Policy*, *160*, 112682.

Robinson, J. (1979). The generalisation of the general theory. In *The generalisation of the general theory and other essays* (pp. 1–76). Springer.

Robinson, S. (1989). *Computable general equilibrium models of developing countries: Stretching the neoclassical paradigm*.

Robinson, S. (1991). Macroeconomics, financial variables, and computable general equilibrium models. *World Development*, *19*(11), 1509–1525.

Robinson, S. (2006). Macro models and multipliers: Leontief, Stone, Keynes, and CGE models. *Poverty, Inequality and Development: Essays in Honor of Erik Thorbecke*, 205–232.

Robinson, S., & Lofgren, H. (2005). Macro models and poverty analysis: Theoretical tensions and empirical practice. *Development Policy Review*, *23*(3), 267–283.

Rosenbloom, D., Markard, J., Geels, F. W., & Fuenfschilling, L. (2020). Why carbon pricing is not sufficient to mitigate climate change—And how "sustainability transition policy" can help. *Proceedings of the National Academy of Sciences*, *117*(16), 8664–8668.

Rotemberg, J. J., & Woodford, M. (1993). *Dynamic general equilibrium models with imperfectly competitive product markets*. National Bureau of Economic Research Cambridge, Mass., USA.

Sadraoui, T., Hamlaoui, H., Youness, Z., & Sadok, B. (2019). A dynamic panel data analysis for relationship between energy consumption, financial development and economic growth. *International Journal of Econometrics and Financial Management*, *7*(1), 20–26.

Saelim, S. (2019). Carbon tax incidence on household demand: Effects on welfare, income inequality and poverty incidence in Thailand. *Journal of Cleaner Production*, *234*, 521–533.

Shahsavari, A., & Akbari, M. (2018). Potential of solar energy in developing countries for reducing energy-related emissions. *Renewable and Sustainable Energy Reviews*, *90*, 275–291.

Shobande, O., Uddin, G., & Ashogbon, F. (2020). *General equilibrium modelling: The state of the art*.

Shoven, J. B., & Whalley, J. (1992). *Applying general equilibrium*. Cambridge university press.

Steckel, J. C., & Jakob, M. (2021). The political economy of coal: Lessons learnt from 15 country case studies. *World Development Perspectives*, *24*, 100368.

Stern, D. I. (2011). Elasticities of substitution and complementarity. *Journal of Productivity Analysis*, *36*, 79–89.

Stern, N., & Stiglitz, J. E. (2021). *The social cost of carbon, risk, distribution, market failures: An alternative approach* (Vol. 15). National Bureau of Economic Research Cambridge, MA, USA.

Stiglitz, J. E., Stern, N., Duan, M., Edenhofer, O., Giraud, G., Heal, G. M., La Rovere, E. L., Morris, A., Moyer, E., Pangestu, M., & others. (2017). *Report of the high-level commission on carbon prices*.

Taylor, L. (1990). Structuralist CGE models. *Socially Relevant Policy Analysis. Structuralist Computable General Equilibrium Models for the Developing World. Cambridge, Mass*.

Taylor, L., & Lysy, F. J. (1979). Vanishing income redistributions: Keynesian clues about model surprises in the short run. *Journal of Development Economics*, *6*(1), 11–29.

Tesfatsion, L. (2006). Agent-based computational economics: A constructive approach to economic theory. *Handbook of Computational Economics*, *2*, 831–880.

The International Renewable Energy Agency (IRENA). (2020). *Renewable Energy Statistics 2020*. /-/media/Files/IRENA/Agency/Publication/2020/Jul/IRENA_Renewable_Energy_Statistics_2020.pdf?rev=3a5e14b11fe6434dbc3e59b7bbacd6e7

Timilsina, G. R. (2022). Carbon taxes. *Journal of Economic Literature*, *60*(4), 1456–1502.

Treacy, M., & Wiersema, F. (1993). Customer intimacy and other value disciplines. *Harvard Business Review*, *71*(1), 84–93.

Tvinnereim, E., & Mehling, M. (2018). Carbon pricing and deep decarbonisation. *Energy Policy*, *121*, 185–189. https://doi.org/10.1016/j.enpol.2018.06.020

Verme, P. (2017). *Subsidy reforms in the Middle East and North Africa region: A review*. Springer.

Verme, P., & Araar, A. (2017). The Quest for Subsidy Reforms in the Middle East and North Africa Region. *Washington DC: World Bank*.

Wesseh Jr, P. K., & Lin, B. (2016). Refined oil import subsidies removal in Ghana: A ‘triple’win? *Journal of Cleaner Production*, *139*, 113–121.

Wesseh Jr, P. K., & Lin, B. (2017). Options for mitigating the adverse effects of fossil fuel subsidies removal in Ghana. *Journal of Cleaner Production*, *141*, 1445–1453.

Wesseh Jr, P. K., Lin, B., & Atsagli, P. (2016). Environmental and welfare assessment of fossil-fuels subsidies removal: A computable general equilibrium analysis for Ghana. *Energy*, *116*, 1172–1179.

Willenbockel, D., Hoka Osiolo, H., & Bawakyillenuo, S. (2017). *Exploring the Macroeconomic Impacts of Low-Carbon Energy Transitions: A Simulation Analysis for Kenya and Ghana*.

Windrum, P., Fagiolo, G., & Moneta, A. (2007). Empirical validation of agent-based models: Alternatives and prospects. *Journal of Artificial Societies and Social Simulation*, *10*(2), 8.

Winter, S., & Schlesewsky, L. (2019). The German feed-in tariff revisited-an empirical investigation on its distributional effects. *Energy Policy*, *132*, 344–356.

Xia, F., Lu, X., & Song, F. (2020). The role of feed-in tariff in the curtailment of wind power in China. *Energy Economics*, *86*, 104661.

Xie, Y., Liu, X., Chen, Q., & Zhang, S. (2020). An integrated assessment for achieving the 2 C target pathway in China by 2030. *Journal of Cleaner Production*, *268*, 122238.

Yoshino, N., Taghizadeh–Hesary, F., & Nakahigashi, M. (2019). Modelling the social funding and spill-over tax for addressing the green energy financing gap. *Economic Modelling*, *77*, 34–41.

Yu, C.-H., Wu, X., Lee, W.-C., & Zhao, J. (2021). Resource misallocation in the Chinese wind power industry: The role of feed-in tariff policy. *Energy Economics*, *98*, 105236.

Zhang, R., Ni, M., Shen, G. Q., & Wong, J. K. (2019). An analysis on the effectiveness and determinants of the wind power Feed-in-Tariff policy at China's national-level and regional-grid-level. *Sustainable Energy Technologies and Assessments*, *34*, 87–96.

Zhao, Y., Zhou, Z., Zhang, K., Huo, Y., Sun, D., Zhao, H., Sun, J., & Guo, S. (2023). Research on spillover effect between carbon market and electricity market: Evidence from Northern Europe. *Energy*, *263*, 126107.

APPENDIX

Appendix A: Ghana's economy in the base year CGE model

Table A1: Ghana national income statistics from baseline CGE model

Item	Value (GHS billion)	Percentage of GDP
Absorption	181.293	110.534
Private consumption	109.582	66.8115
Fixed investment	38.8531	23.6886
Changes in stock	8.31006	5.06661
Government expenditure	24.5484	14.967
Exports	61.9199	37.7523
Imports	-79.1969	-48.2861
GDP at market prices	**164.016**	**100**
Net taxes	16.4286	10.0165
GDP at basic prices	**147.588**	**89.9835**

Source: Nkrumah (2024)

Table A2: Macro SAM from base CGE model (GHS billion)

		1	2	3	4	5	6	7	8	9	10	11	12
Activities	1		273.82		9.33								283.15
Commodities	2	135.56			100.25	24.55	61.92	47.16					369.44
Factor	3	147.59											147.59
Households	4			148.47	71.49	4.04	5.65						229.65
Government	5						1.05		8.83	6.43	0.25	9.76	26.31
Rest of world	6		79.20	-0.88									78.32
Savings-investment	7				39.75	-2.28	9.69						47.16
Sales tax	8				8.83								8.83
Import tax	9		6.43										6.43
Export tax	10		0.24										0.25
Commodity tax	11		9.76										9.76
Total[10]	12	283.15	369.44	147.59	229.65	26.31	78.32	47.16	8.83	6.43	0.25	9.76	

Source: Nkrumah (2024)

[10] Summation of rows and columns may differ from 'Total' values due to rounding errors

Table A3: Snapshot of Ghana's economic structure in the base year, 2015

	Value-added share	Production share	Employment share	Exports share	Export-Output share	Imports share	Imports-demand share
Export crops	2.10228	1.27785	3.12899	1.35343	16.3924	0.0336429	1.45855
Food crops	20.3521	12.0414	18.3133	1.83569	4.22947	2.51647	8.77992
Other agric products	2.02087	1.6591	1.11976	0.10471	1.38017	0.0947168	1.81324
Mining & extractive products	8.22302	14.9097	8.7106	50.7161	74.3866	1.63249	10.8608
Non-agric food processing	2.03871	5.0975	1.82892	5.03029	25.2751	10.3263	51.2727
Petroleum	1.23733	2.67163	0.121283	0.664511	5.4393	0.731186	8.06037
Hydroelectricity	0.358463	1.59015	0.1541			0.0100321	0.176151
Thermal electricity	0.904017	1.88647	1.47567			0.0112666	0.166768
Solar photovoltaic	0.0132062	0.0136682	0.0257773				
Other industries	22.7185	19.5265	10.3242	9.46924	10.6049	57.5889	50.2579
Services	40.0315	39.326	54.7974	30.826	17.1418	27.055	18.8467
Total	**100**	**100**	**100**	**100**	**22.5241**	**100**	**28.7554**
Total Agriculture	24.4752	14.9783	22.562	3.29382	5.09967	2.64483	7.24264
Total non-agriculture	75.5248	85.0217	77.438	96.7062	25.0937	97.3552	31.7143

Source: Nkrumah (2024)

Appendix B: Snapshots of codes of the CGE model in the GAMS Studio software

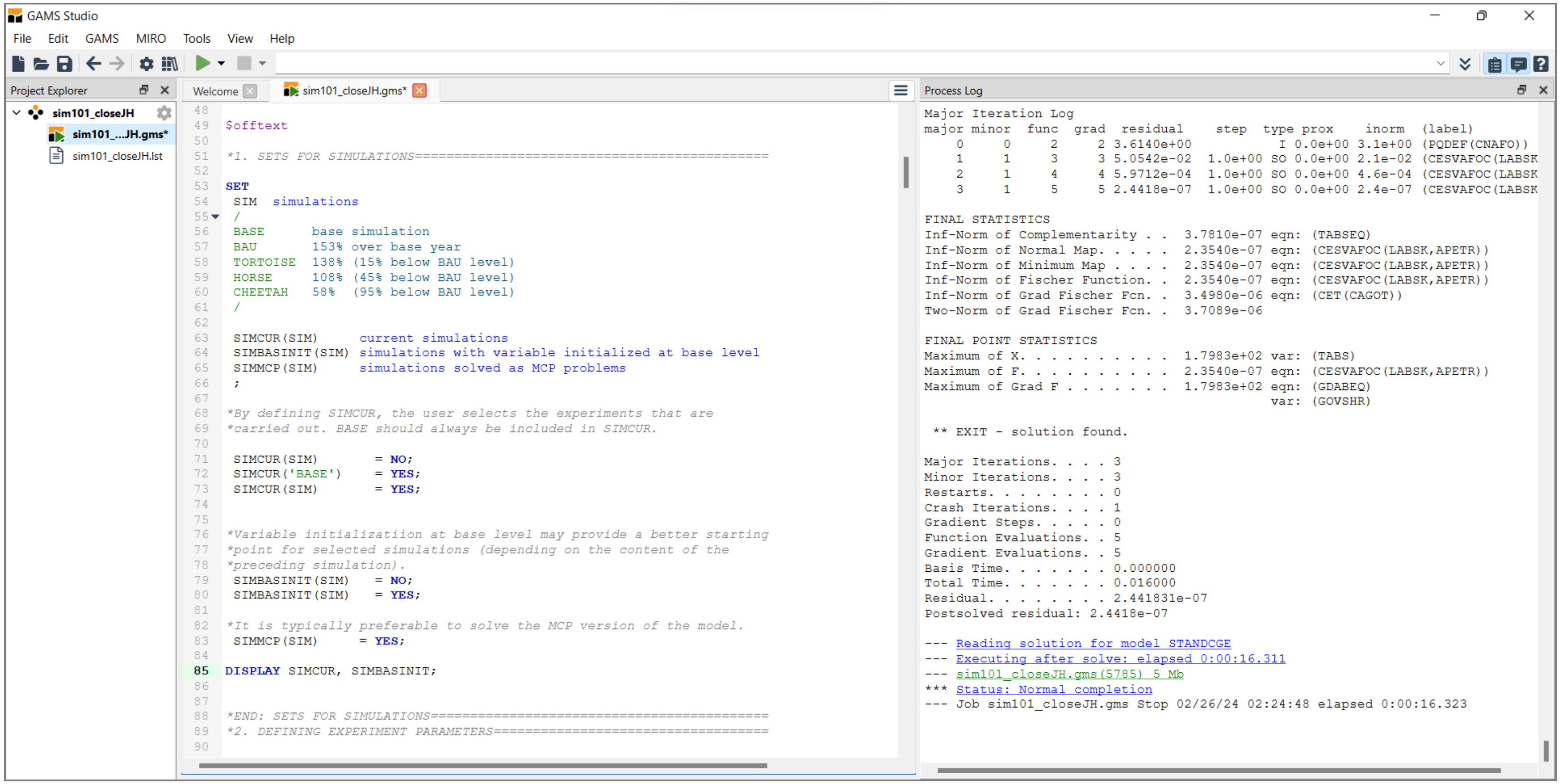

Figure B1: Snapshot of simulation set-up (declaration of sets) in GAMS Studio
Source: Nkrumah (2024)

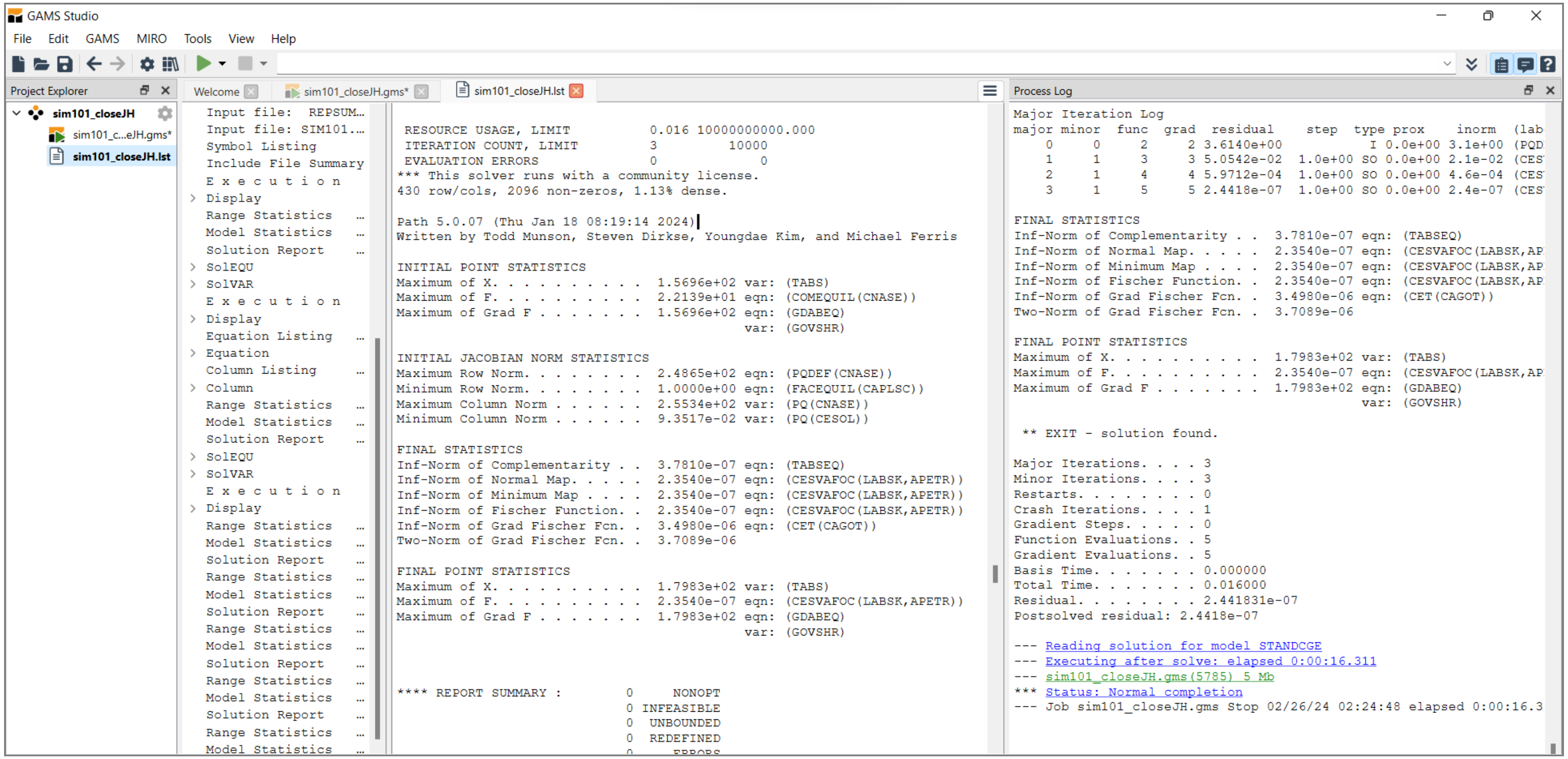

Figure B2: Snapshot of model statistics after solving successfully

Source: Nkrumah (2024)

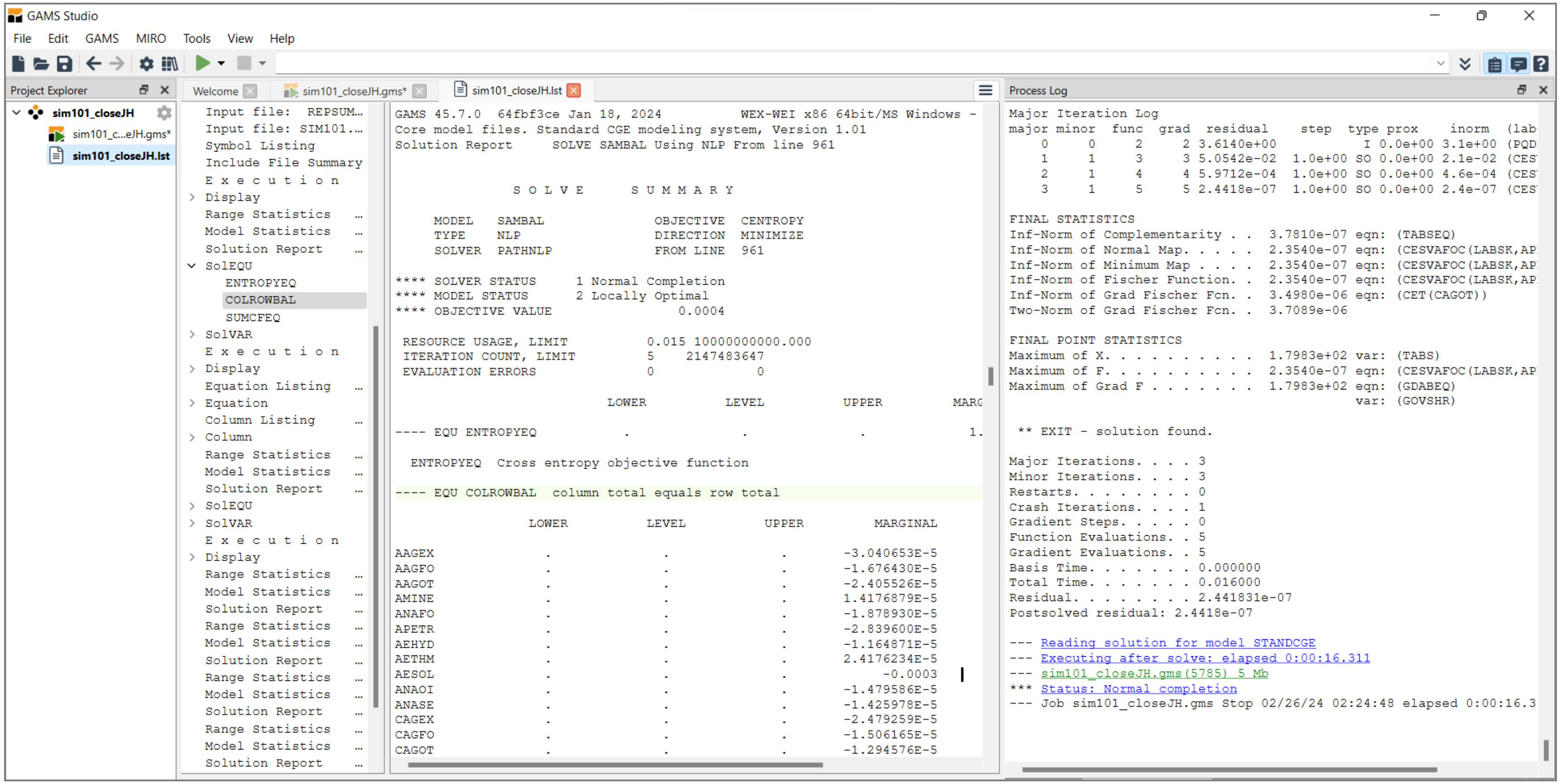

Figure B3: Snapshot of solution report in GAMS Studio

Source: Nkrumah (2024)

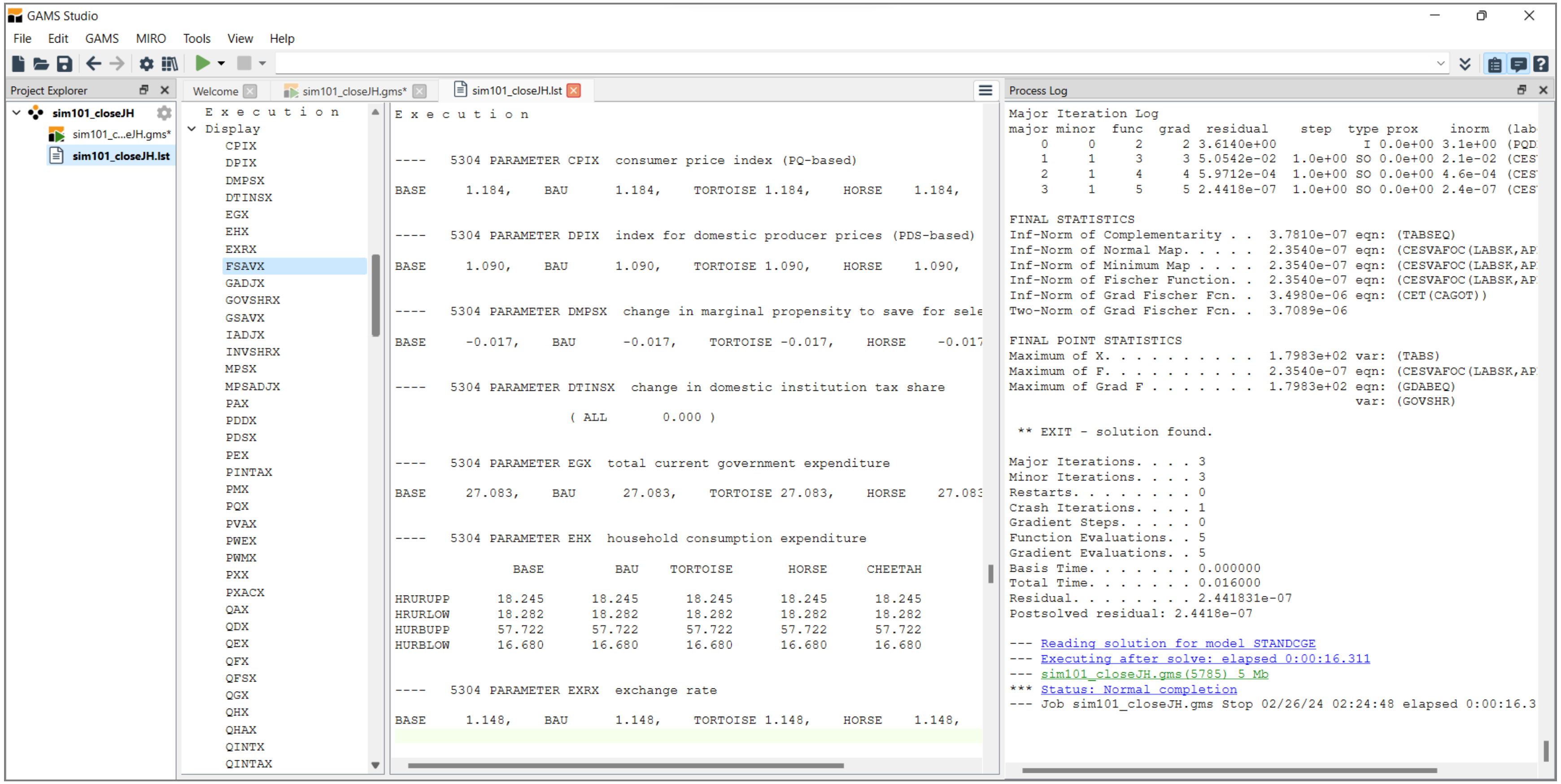

Figure B4: Snapshot of model solution in GAMS Studio.

Source: Nkrumah (2024)