

Macroeconomic effects of a low carbon electrification of greater Kampala Metropolitan area energy policy: A computable general equilibrium analysis

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ABSTRACT

Greater Kampala Metropolitan Area (GKMA) is Uganda's capital facing increasing pressures to raise electricity generation and also mitigate CO₂ emissions. A low-carbon electrification of the GKMA energy policy is proposed for sustainability. But the macroeconomic effects of this policy are unknown. The study uses a multi-sector, single region, static GKMA-CGE model to address the knowledge gap in 4 scenarios. BAU is the baseline against which comparisons with Kabejja (20% CO₂ abatement); Carbon-Tax (\$100/ton) and Lutta scenarios (95% CO₂ abatement) are made. The results indicate GDP increased by Kabejja:0.7%; Carbon-Tax:1.3%; Lutta:1.56% with respect to BAU. Equivalent variation also increased compared to BAU. Energy & CO₂ intensities of GDP decreased in all scenarios. The study recommends Lutta for a sustainable 2050.

1. Introduction

The greatest concern to humanity today is global warming caused mainly by CO₂ emissions from the combustion of energy resources [1–3]. In the face of this anthropogenic climate change, Greater Kampala Metropolitan Area (GKMA)'s CO₂ emission-intensive growth poses a serious challenge to the global CO₂ mitigation efforts. However, from an equity point of view, GKMA similar to other Sub-Saharan emerging economies is pushing an ambitious economic drive to catch up with the already developed economies. But these economic initiatives are associated with the use of refined fossil fuels and woody biomass that generate a vast amount of CO₂ emissions in the atmosphere, resulting in a notorious haze and global warming.

GKMA is Uganda's commercial, social and industrial hub, with a population of 4.1 million residents and a key center and driver of economic growth in the East African region. It contributes approximately 60% of Uganda's GDP and accounts for 80% of the country's industrial sector. It has a growing urban informal sector comprising of 500 thousand micro-enterprises, that by far employs a greater population of Uganda. GKMA's economy is currently on a promising growth trajectory of 5.8%, with a steady population growth of 3.1%, due to the momentum of urbanization, industrialization and commercialization [4]. Its energy

supply system comprises of hydropower, biomass, solar, peat, and petroleum oils, with biomass currently predominant at 90% in the energy balance. GKMA has an estimated hydropower potential of 2,000 MW along the White Nile, and a sustainable yield of biomass of 50 million tons/year. The metropolitan is located astride the equator, and 5.1 kWh/m²/day of solar energy is incident throughout the year. GKMA depends on imported refined fossil fuels through Mombasa, Kenya for her transportation demand [5].

GKMA transportation sector is expanding at an increasing rate, resulting in nonsensical traffic jams during peak working hours and increased consumption of fossil fuels that emit CO₂ in the atmosphere [6]. The electricity in the energy balance is also insufficiently low and cannot support the metropolitan's economy sustainably towards the mid-century. Further, the use of woody biomass in industrial, commercial, and residential heating is associated with uncontrolled and unquantified CO₂ emissions in the atmosphere [5]. Because of these challenges, the GKMA energy management system remains unsustainable and lacks a focused policy framework. Consequently, the relationship between energy supply and demand, the economy, as well as related environmental concerns have become a major problem for stakeholders [7]. In order to deal with these current energy and environmental challenges that may slow down the economic development in

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the years to come, it has been proposed that the metropolitan adopts the low-carbon electrification of the GKMA energy policy for a sustainable future. This policy advocates for the generation of low-carbon electricity from hydropower & PV-solar renewable sources to increase its share by 53.68% in the energy balance. It also suggests efficiency improvement in demand technologies specifically in transportation; and heating in industrial, commercial, and residential sectors. The policy further recommends setting up an electrified Kampala metro to switch most land passengers from road to railway transportation mode if the metropolitan is to achieve sustainable growth by 2050.

1.1. Background and motivation for the study

The macroeconomic effects of the low-carbon electrification of the GKMA energy policy, being region-specific, are yet to be quantified. The macroeconomic effects of energy policies are region-specific because of variations in GDP, factors of production like capital & labor, availability of primary energy supply resources, and appropriate technologies in world economies [8–12]. These macroeconomic effects of energy policies, such as changes in economic structures, equivalent variation in household welfare, the energy intensity of GDP, and CO₂ emissions intensity of GDP are key economic performance indicators when evaluating the energy management system's transition to low-carbon footprints in societal terms [13–17]. This is because the implementation of an energy policy in the economy triggers investments in new and renewable primary energy sources, energy efficiency measures, alterations in the electricity generation fuel mix for intermediate and primary inputs including labor, changes in fossil fuel demand, and alterations in the aggregated energy demand and associated prices for households [18–20].

There are a few studies addressing the long-term impacts of the low-carbon electrification of the GKMA energy policy, and such studies have only addressed energy impacts such as the total primary energy supply; electricity generation by fuel type; final energy consumption by sector & fuel type; CO₂ emissions by sector & fuel type and the annual system cost using TIMES-VEDA, a bottom-up engineering model. Such studies did not consider the macroeconomic effects of this policy. As such, there is a knowledge gap relating to the macroeconomic effects of this policy and this study addresses it using a computable general equilibrium (CGE) modeling framework. In this regard, a CGE analysis was meritorious in answering the following key planning research questions: 1) How does the low-carbon electrification of the GKMA energy policy affect the economy of the metropolitan by 2050? What is the most suitable CO₂ abatement strategy for GKMA towards the mid-century? Therefore, the purpose of this study is to develop an economic model that examines the macroeconomic effects of the low carbon electrification of the GKMA energy policy on the metropolitan economy using a computable general equilibrium (CGE) framework in four energy scenarios. A reference and three other low-carbon scenarios are used to confront the uncertainty that is inherent in the metropolitan's future energy management system. Business as usual (BAU) is the baseline scenario and it depicts the current status-quo of GKMA's energy management system with less commitment to a low-carbon society towards the mid-century. Kabejja proposes a 20% reduction in CO₂ emissions, Carbon-Tax proposes a carbon tax of 100 S/ton, and Lutta proposes a 95% reduction in CO₂ emissions. These three alternative scenarios present abatement strategies leading to a sustainable 2050 for the metropolitan.

The study adopts a CGE framework because of its ability to capture the entire economy's aggregated supply and demand. The CGE model generator instantaneously adjusts the quantities and relative prices of aggregated supply & demand when subjected to an energy policy shock during a simulation [21]. This study examines the macroeconomic effects of the low-carbon electrification of the GKMA energy policy in terms of change in GDP, equivalent variation in household welfare (income), the energy intensity of GDP, and CO₂ emission intensity of GDP. Several studies, over the years, have used a CGE framework to

determine and examine the macroeconomic effects of energy policies. For example; 1) [22] used a CGE framework to model transportation demand in Swedish households. During their CGE analysis, it was established that in all scenarios; people living in households situate in sparsely populated areas, which are mainly located in the northern parts of Sweden, are more affected by the carbon tax because of their higher car dependency. 2) [23] used the CGE economic model generator to determine the cost of abating CO₂ emissions in Switzerland by integrating mitigation technologies into economic modeling. Their analysis suggests that Switzerland's climate policy will not be able to shift the economy towards the required 10% reduction in CO₂ emissions unless a bottom-up abatement cost curve is included. 3) [24] successfully used the CGE framework to determine the macroeconomic effects of a carbon tax on the Chilean electricity generation sector. During their analysis, it was established that the carbon tax had a negative impact on the Chilean GDP, and the success of this policy will depend on non-conventional renewable energy investment projections, pricing of LNG, and utilization of hydropower resources. 4) [12] used the CGE framework to determine the macroeconomic effects of Lithuanian energy development scenarios in the domestic electricity generation. They concluded that scenarios with higher domestic electricity generation levels might fail to provide substantial economic benefits even though increasing electricity import prices would still create preconditions to increase domestic electricity production and turn Lithuania into a net electricity exporter. 5) [25] used a CGE modeling framework to examine the role of global electrification of the transportation sector in global climate change mitigation scenarios. Their analysis suggests that the sole electrification of the transportation sector without changing the fossil fuel-based power industry results in an increase in carbon emissions. However, switching to an electrified road transportation system under sustainable pathways promises a low-carbon transition, even in the absence of decarbonization of the electricity generation sector. They concluded that penetration of electric vehicles in the transportation industry will reduce the cost of implementing the strategic objective that restricts the global temperature rise to a 2-degree centigrade increase over the century. Therefore, following the same methodology, this study describes the development and first deployment of a GKMA-CGE model to assess the macroeconomic effects of BAU, Kabejja, Carbon-Tax, and Lutta scenarios, in terms of variations in GDP and sectoral growth, equivalent variations (EV) in household welfare (income), the energy intensity of GDP and CO₂ emission intensity of GDP due to implementation of the low-carbon electrification of the GKMA energy policy.

Because macroeconomic effects of energy policies are region-specific [26,27], their quantification for GKMA due to the implementation of this policy is warranted. And the fact that this study is the first top-down approach employing a CGE framework to examine the macroeconomic effects of this policy combined, constitutes novelty. But this approach has limitations of high-level aggregation during modeling making it rather unmanageable to examine comprehensively the technology-specific policy shocks. However, this study mitigates such limitations by using the energy impacts of the GKMA-TIMES model together with the GTAP 10 A 2014 database following [12]. Further, this study makes a significant contribution toward the advancement of the United Nation's sustainable development goals, notably SDG 7 (Affordable and clean energy) and SDG 11 (Sustainable cities and communities). It is also in line with the Paris Low-Carbon Road map, exploring feasible energy management system possibilities that could restrict global warming to a 2-degree temperature rise by the end of the century. The restriction of global temperature to a 2-degree centigrade rise by 2100 is a global sustainable target that aims at reducing the risks and impacts of climate change [28]. This strategy includes among others; coveted efforts that decarbonize the entire energy management system at a metropolitan level. Previous studies have shown that to restrict global warming to a 2-degree temperature rise by the end of the century, meaningful decarbonization initiatives at a local level in transportation, commercial, Industrial, households, and power

generation activities are urgent and necessary [29–37]. Against that background, therefore, this study develops and uses a multi-sector, single region, static computable general equilibrium model, the GKMA-CGE, with specific technology level disaggregation in low-carbon electricity generation and transportation sector for a feasibility analysis of the low-carbon electrification of GKMA energy policy following [38, 39].

The paper is organized as follows; Section 2 describes the methodology of CGE modeling and study approach, the development of the GKMA-CGE model, scenarios setting, a qualitative description of BAU, Kabejja, Carbon-Tax, and Lutta scenarios, and the simulation of the model in GEMPACK. The discussion of the macroeconomic effects of the low carbon electrification of the GKMA energy policy is in section 3. Finally, the key findings of the study are summarized with concluding remarks, recommendations, and policy implications in section 4.

2. Methodology

2.1. CGE modelling and study approach

We use the CGE framework to investigate the macroeconomic effects of BAU, Kabejja, Carbon-Tax, and Lutta energy scenarios on the GKMA energy management system. Based on its nature, the CGE framework captures the economic behavior of major entities in the economy (producers and consumers) as well as the major linkages among production, government, consumption, and the rest of the world [40]. A shock in one variable or parameter triggers changes instantaneously in the entire economy resulting in a new balance [41]. These behavioral characteristics of CGE models make them relevant for this study that analyzes the macroeconomic effects of the low-carbon electrification of the GKMA energy policy.

CGE models are top-down frameworks, derived from the general equilibrium theory of Walras which suggests that supply and demand are balanced across all markets in the economy. They combine the general equilibrium theory of Arrow and Debreu's economic data to solve for supply, demand, and relative prices across a specified set of markets [42]. Although general equilibrium theory deals with the interactions of many households and firms, most CGE models are rather aggregated and a single household suffices as a representation of the entire economy [43,44]. The utility of households and profit maximization of production firms is generally assumed to satisfy Walras' law. However, product and factor markets are assumed to be competitive with relative prices flexible enough to simultaneously clear all product and factor markets. A key difference compared to Leontief's input-output (I-O) framework is that in a typical CGE model the technological coefficients are flexible and determined by relative prices [45–47]. CGE models are sometimes referred to as Applied General Equilibrium (AGE) models. The "Applied" name emphasizes the fact that the database and numerical results are not merely illustrative but rather employ actual data reflective of specific regional situations [48,49]. During simulation, CGE models endogenously determine relative prices but not nominal prices making them useful in quantifying the impacts of energy policies on the economy [50,51].

CGE models are built as static or dynamic and either is applicable in economic analysis of energy policies [43]. The dynamic CGE models are either recursive or forward-looking models [52]. In a forward-looking dynamic model, decisions about production and utility are made based on expectations for all periods over the planning period and are assumed to be known with certainty [53]. A recursive dynamic CGE model is an intermediate approach between the static model and the forward-looking dynamic model and decisions about production and utility are made based on current period variables, a marvel termed myopic expectation [52]. However, a static CGE model adjusts instantaneously the demands and prices in response to external shocks (policy shifts). The reactions in the economy are modeled at only one point in time. For policy analysis, results from a static CGE model are always

interpreted as showing the reaction of the economy in some future period to one or a few external shocks or policy changes [54–56]. The GKMA-CGE is modeled static because the study aims at establishing the macroeconomic effects of the low carbon electrification of the GKMA energy policy by 2050.

During the analysis of a CGE model, a combination of economic theory, econometrics, and the numerical solution is done [57]. A CGE framework, therefore, assembles economic data into a set of mathematical equations with an aim of capturing the structure of the economy and the behavioral response of agents [58]. The mathematical structure of the CGE model, therefore, provides a framework to simulate policy changes and trace the impacts on key macroeconomic variables, including income and expenditure flows [59–61]. CGE models are assembled and simulated using either GAMS or GEMPACK interface [62–64]. GKMA-CGE's mathematical build and simulation follow GEMPACK syntax, a Fortran compiler. GEMPACK simulates accurate solutions of CGE models, starting from an algebraic representation of the model equations which can either level equations or linearized equations, or a mixture of these two. It accepts the equations and formulae of the model in a form that is essentially the same as ordinary algebraic notation. It is ideal for comparative static studies like the macroeconomic effects of the low-carbon electrification of the GKMA energy policy [65].

2.1.1. Uncertainties and limitations of the CGE modeling framework

A CGE modeling framework (top-down approach) is endowed with great strength in areas where bottom-up models such as TIMES show weaknesses, notably the inclusion of macroeconomic feedbacks [66–69]. But the Constant Elasticities of Substitution (CES) parameters that populate the baseline year equilibrium conditions are sourced from literature surveys [70,71] This strong dependence on such historical data has a major drawback of uncertainty [43,58,72]. However, the modeler mitigates the uncertainty in a CGE model, by scenarios planning and carrying out a sensitivity analysis to check for the robustness of the CES values employed and for consistency of the simulation results before policy analysis is done [41,73]. In general terms, the most critical weakness of CGE modeling frameworks is their high level of aggregation making it impossible to evaluate technology-specific policy shocks [74–77]. On the other hand, it is advantageous because data requirements for CGE models are much more limited compared to bottom-up frameworks such as the TIMES model. Given the limitations and strengths of both approaches, and more so the need to develop low-carbon footprints that address global warming, the new norm is to combine them and create a "hybrid" framework. Here, the strategy is either to include a more detailed technology disaggregation in a top-down model following [78–80] and others or to include macroeconomic feedbacks and behavioral parameters in bottom-up models following [12,81–83] and others. This study mitigates the limitations of the CGE model by using the energy impacts of the GKMA-TIMES model together with the GTAP 10 A 2014 database following a similar paradigm.

2.2. The analytic framework of the GKMA-CGE model

GKMA-CGE is a top-down model having an equilibrium reached by various agents simultaneously operating in the respective markets, developed as a single region, multi-sector, static, from energy impacts of GKMA-TIMES model, and the social accounting matrix (SAM) of Uganda aggregated from GTAP10A 2014 database, over a planning period 2015–2050. It consists of four institutions; households, government, rest of the world (ROW) and production firms as shown in Fig. 1 [84–86].

2.2.1. Households

The representative household receives income from the rental of primary factors of production (Capital and Labor) and lump-sum transfer from the government and ROW [87–89]. All the households

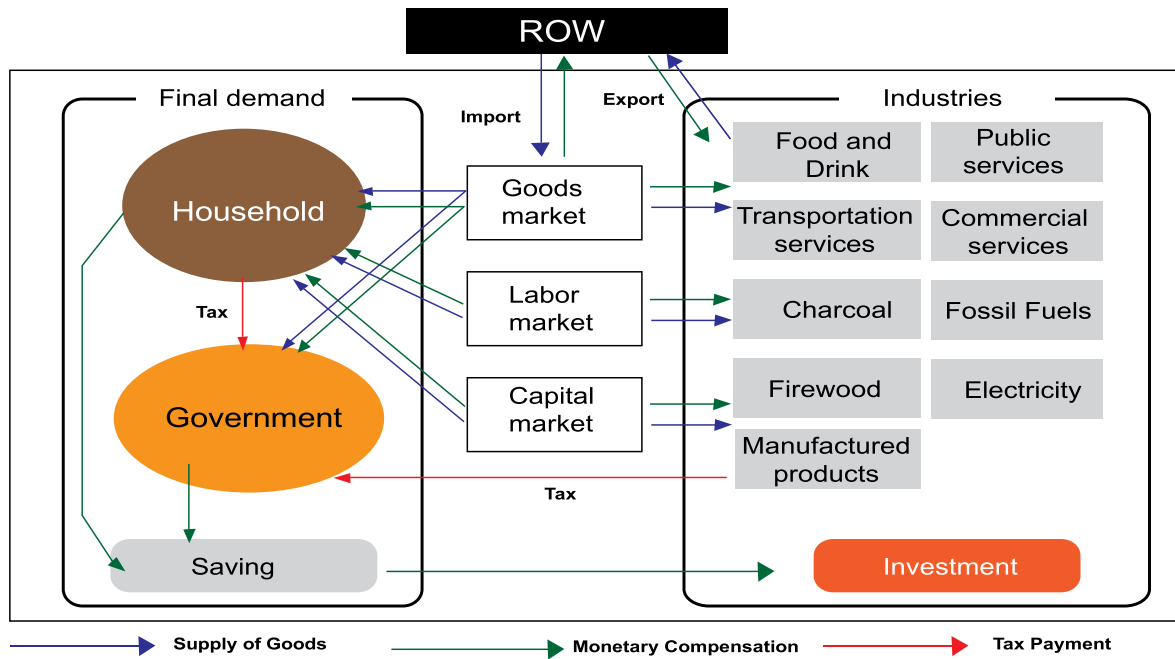


Fig. 1. Gkma -CGE framework.

in GKMA are represented by a single representative household [90]. Household income consists of capital income, labor income, net transfer from the government, and the foreign institution [91]. The income is used for consumption and investment. The model adopts a closure that investment is savings-driven. It is assumed that investment will increase linearly at the same pace as the GDP growth rate during the planning period. Except for investment, the household maximizes its utility by choosing the levels of consumption of commodities, subject to the constraints of its income and commodity prices following a Cobb–Douglas function [87]. The GKMA household is nested as shown in Fig. 2.

2.2.2. The government

The government acts as a final consumer of commodities providing services such as public administration, defense, social security, collecting taxes, and makes the net transfer to the household and capital investment in the metropolitan economy with a CES of a Cobb–Douglas demand function following Hertel & Dominique [92]. Similar to other CGE models, GKMA-CGE assumes a small open economy, small enough for its policies not to alter world prices or income [93]. Goods are distributed to domestic and international markets with the Leontief function [94]. The model adopts a neo-classic approach with full

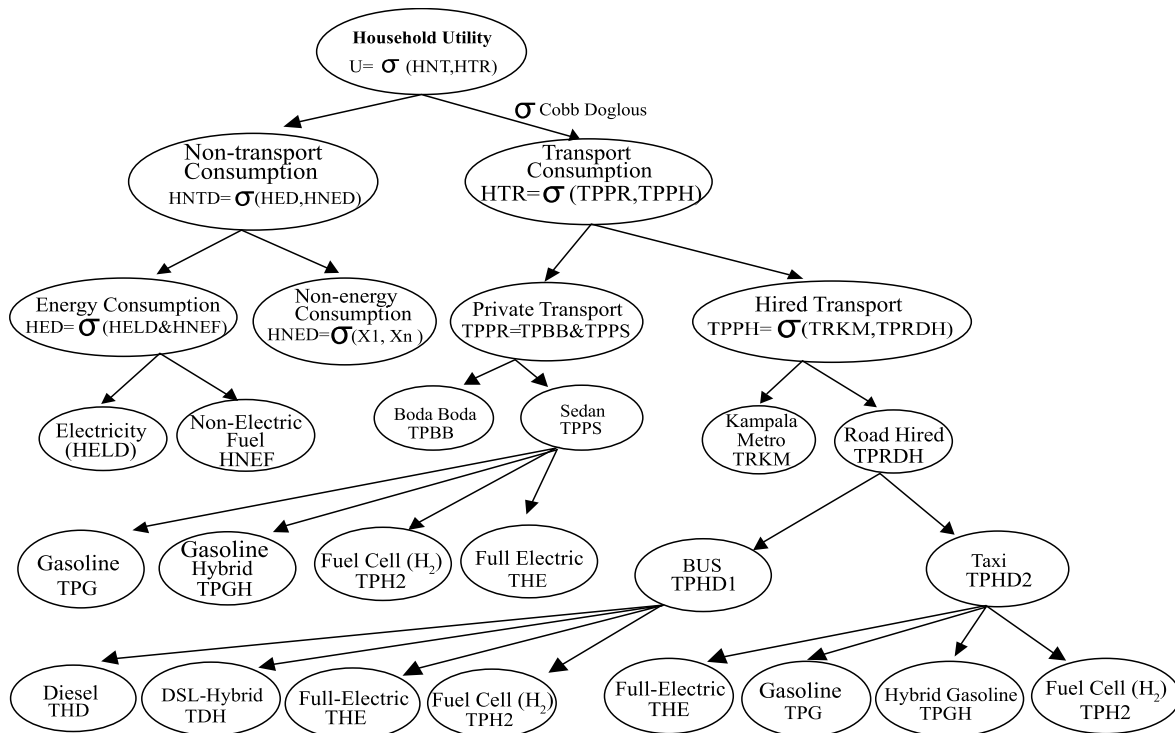


Fig. 2. Nested household structure.

employment of capital and labor supplied by the household in the factor market following the Armington assumption [95,96]. The ROW acts as a foreign agent involved in the trade of commodities and institutional transfer [97–100].

2.2.3. Production sectors

The production module comprises food & drink, manufacturing, commercial services, public services, charcoal, firewood, electricity generation, land freight transportation, and land passenger transportation with specific technology disaggregation in electricity generation and transportation (Table 1). The decarbonization strategy and resulting aggregated strictness of fuel standards for production technologies are determined by the various agents involved. Developers of all key technologies in transportation and low-carbon electricity generation are supplied from ROW.

2.2.4. Low-carbon electrification in the GKMA-CGE model

The low-carbon electrification restructuring is majorly generation represented by a bundle of technologies through an implicit production CES function and depends initially on the government investing heavily in the appropriate technologies prior to the household being certain about market development. The household initially hesitates to uptake the new technologies that come with low-carbon electrification of the transportation sector citing a lack of visibility of clear cost reduction and network availability. To confront the uncertainty inherent in the low-carbon electrification restructuring process, scenarios planning is used. The model assumes that positive externalities from successful harmonization of markets and the availability of low-carbon advanced technologies for low-carbon electricity generation and transportation are key performance indicators to investors about market size over the planning period.

The GKMA-CGE model examines low-carbon electrification by making assumptions about how electricity will be produced from indigenous low-carbon technologies in Uganda and then sold to the metropolitan economy. Each electricity generation technology is an aggregation of costs, resource requirements, CO₂ emissions, and flexibility following [39,101,102,146]. The low-carbon electrification modeling follows a technology bundle approach that disaggregates generation using key calibration parameters from the GTAP 10 A 2014 database, supplemented with data from the GKMA-TIMES model following [103–105]. It considers economic activities related to the life cycle of low-carbon electricity generation such as investment, employment, the uptake of technologies and use of fuels for production, the sale

of low-carbon electricity to end-users, the payment to households for investment, and employment to track the macroeconomic effects of this policy for each scenario employed in the analysis [106,107,147]. This approach disaggregates the electricity sector by distinguishing between generation and non-generation activities, combining the competing generation technologies through a CES function following the standard economic theory that allows differing assumptions about substitutability between technologies, fuels, capital, and labor.

Low-carbon electricity generation technologies are PV-Solar, hydropower, and biomass-fired and are disaggregated to the specific technology levels following Ian [38,39,42,108]. Therefore, the low-carbon electricity generation activity distinguishes between three technologies that are substitutable with constant elasticity of substitution (CES). It is assumed that each specific low-carbon electricity generation technology is of a fixed coefficient production function having a primary factor composite and intermediate inputs [66,87]. Every intermediate input is an aggregate of imported and domestic goods which is represented by a CES function, allowing substitution between imported and domestic goods by employing the Armington elasticity of substitution between imported and domestic goods [47,66,109]. The allocation of the output, inputs, and CO₂ emissions of low-carbon electricity into the technologies, follows the social accounting matrix of the model [42]. The model assumes further that the degree of substitution between any two-competing low-carbon electricity generation technologies is the same [110–112].

Freight land transportation is an intermediate input to production and the passenger land transportation is a final consumption following Schafer & Jacoby [113]; Shahraki & Bachmann [114]; Soleymani & Kari [115]; De Jong et al., [116]; Tavasszy [117]; Karkatsoulis et al. [118]; Henseler & Maisonnave [119]. Land freight and land passenger transportation are further disaggregated into road and rail transportation subsectors with specific technology disaggregation. Freight transportation is represented at the level of specific technology mode (road and railway), transportation category (truck, pickup, Kampala locomotive), fuel type (Diesel, Diesel Hybrid), and prime-mover (internal combustion engine, electric, and hybrid). Passenger land transportation is disaggregated to a specific technology (road and railway), transportation category (sedans, bus, taxi, boda-boda, and Kampala Metro), fuel type (Gasoline, Gasoline Hybrid, Fuel Cell (H₂), and electricity, and prime mover (internal combustion, hybrid or full-electric). Transportation services comprise fixed ratio intermediate inputs and factors composition following [120]. A total of nine commodities are produced with four imported fossil fuels as intermediate energy input commodities and are incorporated into the social accounting matrix (SAM).

The behavior of each production sector is represented by a nested production function structure following Burinaux and Truong [121–123] with profit maximization. The producing firms minimize their costs of production for each level of the output, competing among themselves for the common factors of production (Capital and Labor). Activity output of each sector follows a nested constant elasticity of substitution (CES) determined by a fixed coefficient aggregation of non-energy intermediate commodities, primary factors, and energy intermediate commodities for material use (Fig. 3). The composite of non-energy inputs follows a Leontief function. The primary factors composite is a CES aggregation of labor and capital-energy bundle following a Cobb–Douglas function. Capital is substitutable with the composite of energy inputs with a substitution elasticity of 0.3. Capital and labor are fully employed, perfectly mobile, and competitive. The composite of energy inputs is a CES aggregation of electricity, Charcoal, firewood, and fossil fuels with the elasticity of substitution of 0.3. Fossil fuels are disaggregated into Gasoline, Diesel, Kerosene, and LPG with the elasticity of substitution of 1.5 following Yahoo & Othman [124]. The non-competitive refined fossil fuels are intermediate input commodities and are supplied from imports only.

GKMA-CGE is built on a basic modular platform, with modeling routes, market regimes, and closure rules supported by similar model

Table 1
Production sectors and commodities in the model.

Item	Production sectors	Imported/Produced commodities
1	Non- Energy	Public Service
2		Manufacturing
3	Food & Drink	Food & Beverages
4	Commercial	Commercial Services
5	Energy	Electricity generation (PV-Solar, hydropower & Biofuels)
6		Charcoal
7		Firewood
8	Transportation	Land freight transportation: road and railway transportation services
9		Land passenger transportation: road and railway transportation services
	Intermediary	Imported fossil fuels
		Diesel
		Gasoline
		Kerosene
		LPG

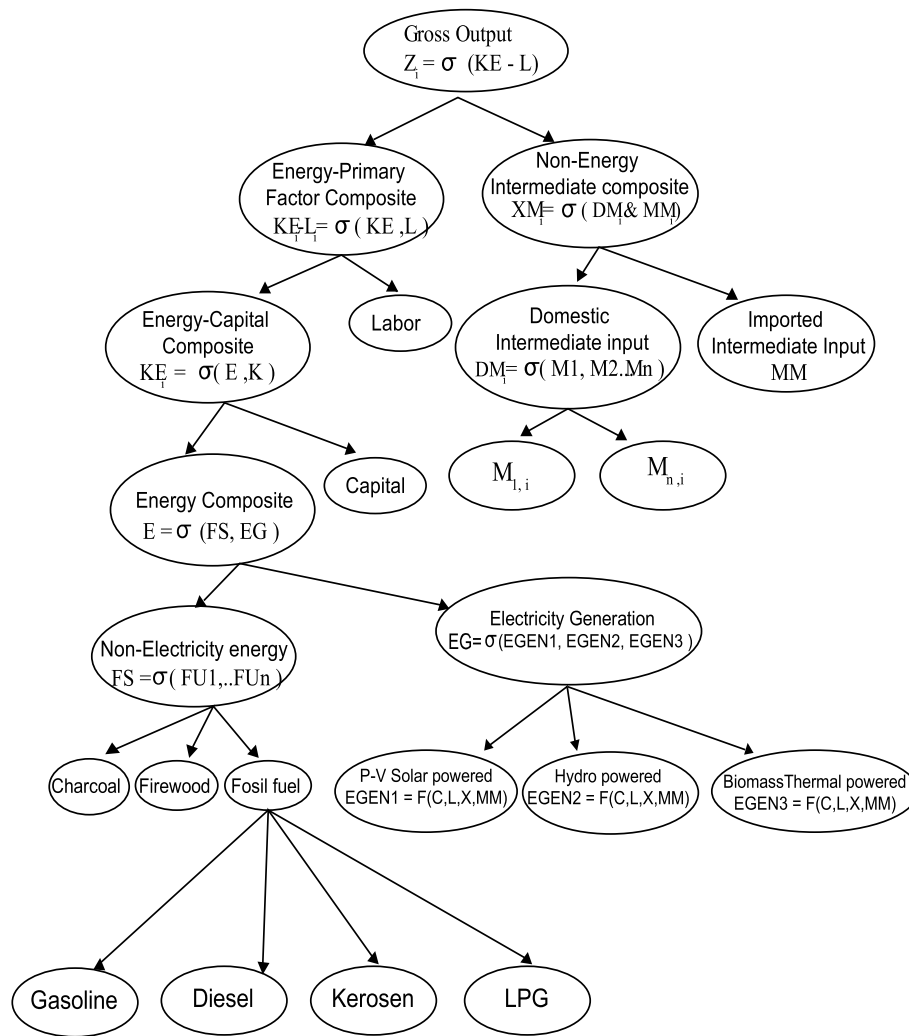


Fig. 3. Production structure.

specifications following [125–127]. All endogenous coefficients are flexible and the calibration of the baseline year is from a well-detailed Social Accounting Matrix of Uganda in the GTAP10A 2014 database and GKMA-TIMES model. Capital letters denote endogenous variables and the small letters designate the exogenous variables. Greek symbols represent the exogenous parameters with subscript ‘i’ representing production activities and the subscript ‘cm’ representing commodities. The current account is assumed to be a constant share of the gross metropolitan product. Imports into GKMA are modeled according to the Armington assumption and all exports are sold at an exogenous world-market price with infinite demand. All prices and the exchange rate are numeraires.

2.3. The social accounting matrix (SAM) of GKMA

The model is calibrated to a SAM reflecting the input-output structure of production, demand, and income distribution for the metropolitan at a disaggregated level following Thorbecke, [128]; Patridge & Rickman, [129]; Thorbecke, [130]. The SAM is constructed from the input-output matrix of Uganda in the GTAP10A 2014 database. The low-carbon electricity generation, transportation, household, and ROW in the SAM are disaggregated as discussed in the analytic framework. Elasticities of substitution are sourced from literature surveys following Wang et al., [131]; Karplus et al., [132]; Yahoo & Othman [124]. Table T1 in the appendix shows the aggregated GKMA-SAM representing the summarized figures of different accounts and the role of different

institutions in the circular flow of commodities and factors in the equilibrium condition of the economy.

2.4. Scenarios settings

We implement the low-carbon electrification of the GKMA energy policy in each scenario by solving for a carbon price path such that the low-carbon electricity generation and other production sectors achieve a specified CO₂ emissions reduction by 2050 following, [133–137]. This is done by guaranteeing the CO₂ emissions reductions over the planning horizon to be consistent with the policy scenario settings specified as a target reduction. The carbon price changes according to the scenario policy settings and is interpreted either as a carbon tax or the market price of CO₂ emissions permits in the GKMA economy [138–140]. The strategy here is to mimic a perfect behavior of an efficient market that allows for depositing and borrowing CO₂ emissions permits, which results in minimization of the business cost of carbon abatement.

The four scenarios used to examine the macroeconomic effects of the low-carbon electrification of the GKMA energy policy are described qualitatively below.

- BAU

BAU is the reference scenario with no policy restrictions on CO₂ emissions and no efficiency improvements that could result in low-carbon electrification of the GKMA energy policy. Labor factor growth

follows the population growth trajectory of the metropolitan. In addition, energy efficiency and capital productivity improvement constitute technical progress. The future capital factor is a function of depreciated capital and new investment based on the previous year. BAU also serves as a benchmark against which policy comparisons with three other low-carbon energy scenarios are made.

- Kabejja Scenario [CO₂-20]

A 20% CO₂ emissions reduction energy scenario in which a carbon price path achieves carbon emissions reductions over the planning horizon to be at least 20% below BAU levels in 2050, decreasing linearly. Kabejja presents a situation where there is a moderate urgency to move the metropolitan to a low-carbon economy by mid-century with other variables remaining similar to BAU.

- Carbon-Tax Scenario

Is a low-carbon scenario with a carbon price path interpreted as a carbon tax of a policy scenario target setting of US\$100/ton in 2050, starting from US\$25/ton in 2020 increasing linearly at a nominal rate each year, to that level with other variables remaining similar to BAU.

- Lutta Scenario [CO₂-95]

Lutta is a 95% CO₂ emissions reduction scenario in which a carbon price path achieves carbon emissions reductions over the planning horizon to be 95% below BAU levels in 2050, and the carbon price increasing linearly. Lutta proposes consistent CO₂ emissions reductions over the planning period that meet the specified target of a 95% reduction in BAU levels by 2050. This pathway includes specific interim targets in line with the Paris Low Carbon Roadmap.

2.5. Model simulation

The model is developed, set up, and simulated in GEMPACK as illustrated in [figure F1](#) of the appendix. Initially, four scenarios were set up with distinct key energy impacts and assumptions on CO₂ emissions mitigation to drive the carbon price path as a scenario target derived from GTAP 10 A 2014 database and GKMA-TIMES model following [12] for reliability of simulation results. Next, GKMA's actual economy was transformed into a simplified one to formulate an economic model structure. Then, GKMA-CGE was formulated from GKMA-SAM by first establishing the equilibrium conditions using BAU as the baseline, thoroughly checking and reviewing BAU's appropriateness to draw equilibrium conditions such as the zero profit, market clearance, and income balance on the basis of the utility maximization of the household and profit maximization of the production firm. The Armington assumption, Leontief function, and Cobb-Douglas function were applied where appropriate. Finally, macroeconomic effects per scenario were evaluated and then compared as percentage values with respect to the baseline scenario. The scenario results were only confirmed when the simulation results and the real economy were consistent. This was achieved through performing a sensitivity analysis on the model results [131,141–144]). The results were then presented for policy analysis and discussion as explained in section 3.

Table 2
Macroeconomic effects of the Baseline Scenario.

Item	2015	2017	2020	2025	2030	2035	2040	2045	2050
GDP (US\$ bn)	23.5	26.19	33.71	45.1 17	61.95	78.84	106.19	141.24	185.02
Consumption (% as GDP)	65.47	63.9	63.7	64.2	64.2	64.6	64.1	65.1	63.8
Imports (% as GDP)	25.5	26.3	26.2	25.1	24.3	24.0	24.5	23.7	24.9
Exports (% as GDP)	9.03	9.8	10.1	10.7	11.5	12.6	11.4	11.2	11.3
Equivalent Variation (Welfare)		0.04	0.09	0.32	0.42	0.51	0.69	0.77	0.82

3. Scenario analysis for macroeconomic effects

3.1. Analysis of the baseline scenario (BAU)

The nominal GDP of GKMA is estimated to grow from US\$ 23.4 billion to US\$ 185 billion. The share of domestic consumption in the household and government is the biggest contributor to GDP throughout the planning period ([Table 2](#)). The equivalent variation (EV) in household welfare increases steadily during the planning period indicating improvements in the metropolitan income compared to the base year conditions. Therefore, there would be a positive growth of real income in the metropolitan household relative to the base year conditions. The imports into the metropolitan are stable throughout the planning period, contributing about 25% to GDP and most of the imported items (38.2%) support the food & drink, 30.5% is intermediate (fossil fuels), 18.6% is manufacturing and motor vehicle spares is 12.7% of Imports. The results further indicate that the metropolitan will export less (11% of GDP) during the planning period because most of the production is consumed domestically.

The total gross output from production sectors increases 7.7 folds from US\$ 21.3 Billion to US\$ 163 Billion ([Table 3](#)). A major growth is registered in the electricity generation and transportation sectors. The economy becomes more enthusiastic when more low-carbon electricity is generated and supplied to the market. Transportation consumes more of the low-carbon electricity, majorly in the Kampala metro, contributing more to the sectoral output of the metropolitan. Food & drink dominates sectoral output to cater for the growing population that comes as a result of increasing urbanization, commercialization, and industrialization during the planning period. The sectoral composition of total gross output increases though with a decrease in public services and manufactured products.

The total gross value from capital and labor employment increases by 8 folds from US\$15.7bn to US\$ 124.45bn ([Table 4](#)). Electricity generation and transportation show significant growth in labor and capital compared to the base year conditions. This is because the government invests heavily in the construction of hydropower dams, PV-solar power plants, and the establishment of the electrified Kampala metro during the planning period. Also, the increasing activities for low-carbon electricity generation and the setting up of the electrified Kampala metro accounts for the major increase in demand for labor over the planning period because such activities are labor-intensive. Transportation, electricity generation, and food & drink continue to dominate in the contribution of gross value added to the economy in the long run.

Therefore, GKMA's economy is expected to be more of services delivery than manufacturing, and this appears to be a plausible trend since GKMA is a developing economy in the phase of industrialization, urbanization, and commercialization.

The analysis further indicates that GKMA would move towards less energy and CO₂ emission-intensive economy in the years to come ([Table 5](#)). The energy demand increases indicating an increase in population and economic activities, but the energy intensity of GDP decreases as GKMA acquires advanced technologies of profound efficiency during the planning period. However, the CO₂ emissions intensity of GDP decreases at a faster rate compared to the energy intensity of GDP. This comes as a result of future uptake of low-carbon electricity that replaces biomass for heating in households, food & drink, manufactured

Table 3
Share of sectoral output for the Baseline Scenario.

Sector (% Gross output)	2015	2017	2020	2025	2030	2035	2040	2045	2050
Transportation	18	18.5	16.2	18.02	22.2	24.8	24.8	25.0	25.5
Manufactured products	12	12.3	10.9	11.2	11.3	11.2	9.5	9.3	9.0
Public services	28	26.1	28.5	17.38	13.15	7.6	9.19	7.6	7.6
Food & Drink	29	29.3	30.1	31.5	30.9	31.1	30.5	31.7	31.6
Commercial services	9.7	10.0	9.8	10.1	10.15	10.2	10.4	10.5	10.4
Electricity generation	3.3	3.8	4.5	11.8	12.3	15.1	15.61	15.9	15.9
Total gross output (US\$ bn)	21.3	24.56	29.55	40.26	51.62	71.50	100.08	136.00	163.00

Table 4
Gross value added (Capital and Labour) by sector for the Baseline Scenario.

Sector (% Gross output)	2015	2017	2020	2025	2030	2035	2040	2045	2050
Transportation	18	18.5	16.2	19.7	20.2	22.4	22.3	22.8	23.0
Manufactured products	10	11.7	10.3	10.9	10.9	10.8	9.0	8.5	8.3
Public services	30	26.8	28.7	16.7	16.3	13.6	14.49	13.4	13.7
Food & Drink	29	29.3	30.1	30.5	30.0	29.7	29.8	30.0	29.4
Commercial services	9.7	9.9	9.8	9.9	10.1	10.1	10.2	10.3	10.2
Electricity generation	3.3	3.8	4.5	12.3	12.5	13.4	14.21	15.0	15.4
Total gross output (US\$ bn)	15.7	19.08	23.5	32.94	44.13	60.65	88.05	119.30	124.45

Table 5
Energy and emission intensities of GDP for the Baseline Scenario.

Item	2015	2017	2020	2025	2030	2035	2040	2045	2050
Final Energy Consumption (PJ)	139.6	271.67	285.51	313.93	343.97	379.4	411.98	459.09	497.42
Total CO ₂ emissions (Mtn)	4622.55	4353.9	4115.17	3818.09	3975.2	4305.37	5176.63	6473.72	6990.04
GDP (US\$ bn)	23.5	26.19	34.71	46.17	60.95	79.84	106.19	141.24	185.02
Energy intensity (PJ/US\$)	5.94	10.37	8.22	6.93	5.64	4.75	3.88	3.25	2.69
CO ₂ intensity (Mtn/US\$ bn)	196.7	166.24	118.56	82.70	65.22	53.93	48.75	45.84	37.78

products; and fossil fuels in the transportation sector.

3.2. Results from the scenario analysis

The scenario analysis presents results on the macroeconomic effects

of the low-carbon electrification of the GKMA energy policy on production sectors, equivalent variation in household welfare, the energy intensity of GDP, and CO₂ emissions intensity of GDP for Kabejja, Carbon-Tax, and Lutta scenarios with respect to BAU. The results are presented as percentage changes relative to the economy’s baseline

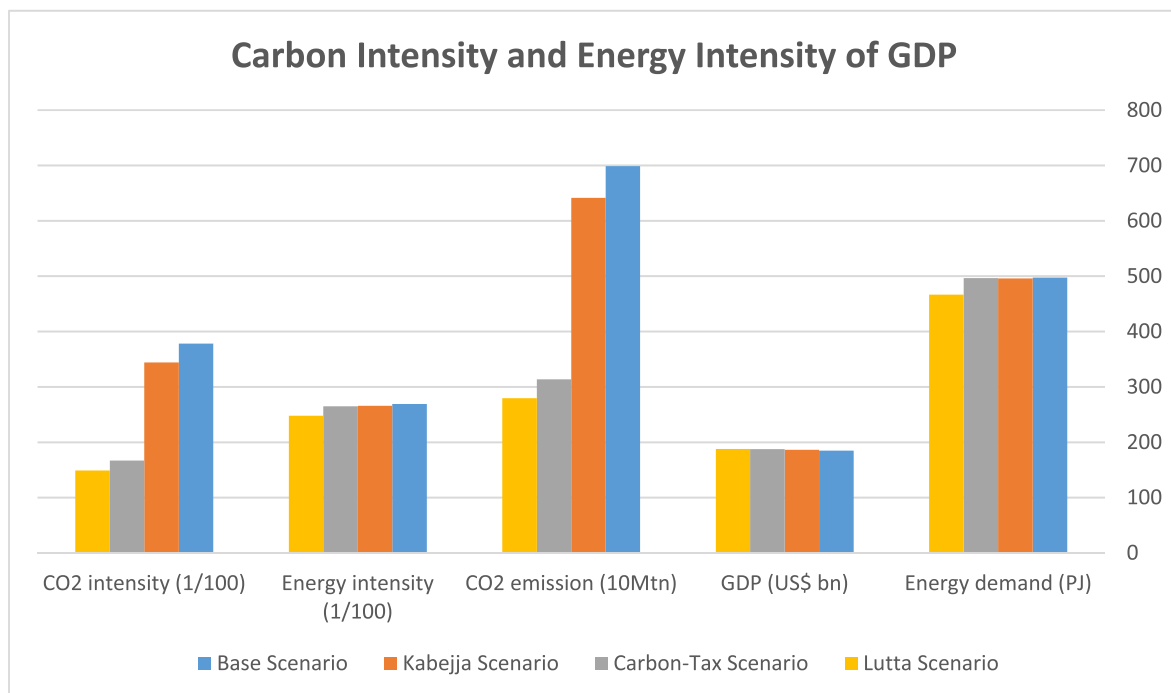


Fig. 4. Carbon intensity and energy intensity of GDP by 2050.

conditions.

3.2.1. Carbon Intensity of GDP and energy intensity of GDP

The energy intensity of GDP decreases by Kabejja:1.1%; Carbon-Tax:1.48% and Lutta:7.8% as compared to BAU whereas CO₂ emissions intensity of GDP decreases by Kabejja:8.9%; Carbon-Tax:55.7% and Lutta:60.6% as compared to BAU (Fig. 4). The energy intensity of GDP decreases as you move towards Lutta because of improvements in both direct & indirect energy intensity of deployed technologies. The specific lower levels of energy intensity of GDP in the passenger land transportation seem more realistic. This is because of improvements in direct energy intensity that come as a result of fuel switching from refined fossil fuels to low-carbon electricity when the household uses the electrified Kampala metro. However, indirect energy intensity accounts for a major share in the food & drink industry, manufactured products such as iron & steel, and residential heating indicating a need to control the use of energy-intensive charcoal & firewood fuels. The CO₂ emission intensity of GDP lowers in all scenarios compared to BAU. This is plausible because there is a substantive reduction in demand for carbon-intensive fuels as the energy management system grabs more of low-carbon electricity in transportation, food & drink, manufacturing, and household heating. This result suggests that a significant decrease in the consumption of Charcoal, firewood, and refined petroleum is necessary, giving way to low-carbon electricity in the household heating and key production sectors for sustainable economic growth. The results further show that a 60.6% reduction in the CO₂ emissions intensity of GDP is plausible in the Lutta scenario, suggesting that the metropolitan adopts the Lutta scenario for a sustainable 2050.

3.2.2. Deviation of real GDP from the baseline conditions

The analysis suggests that real GDP will increase by Kabejja:0.7%; Carbon Tax:1.3% & Lutta:1.56% as compared to the Baseline conditions.

The equivalent variation (EV) in household welfare (income) increases as you move towards Lutta as shown in Fig. 5. The significant increase in real GDP and equivalent variation (EV) in household income for the Lutta scenario as compared to the baseline conditions comes as a result of changes in the distribution and the re-allocation of the factors of production, intermediate inputs, and change in demand due to the implementation of the low-carbon electrification of the GKMA energy policy. The difference in EV is more significant in the transportation and low-carbon electricity generation sectors in all scenarios. This result also suggests that the metropolitan would require a foreign direct investment (FDI) injection towards contribution to the capital factor into the economy for the realization of increased employment and GDP. Low-carbon electricity generation and setting up an electrified Kampala metro are labor-intensive activities that result in a significant increase in equivalent variation (EV) in household welfare (income) in all scenarios as compared to the baseline conditions.

3.2.3. Impacts of Gross Output on Domestic Production Sectors

The study shows an increase in the gross domestic product in all scenarios compared to BAU (Fig. 6), mostly in the transportation sector (Kabejja:3.4%; Carbon Tax:11.9%; Lutta:17.3%). This is because of increased displacements that come as a result of the increasing population and a major shift in resources (low-carbon electricity and labor) from other sectors to the transportation sector to establish the electrified Kampala metro. Electricity generation remains stable in all scenarios indicating a need to increase electricity in the metropolitan's energy balance in all situations. A substantive investment in electricity generation and transportation is key, preferably from FDI to contribute to the capital factor, if the metropolitan is to achieve sustainable economic growth by 2050.

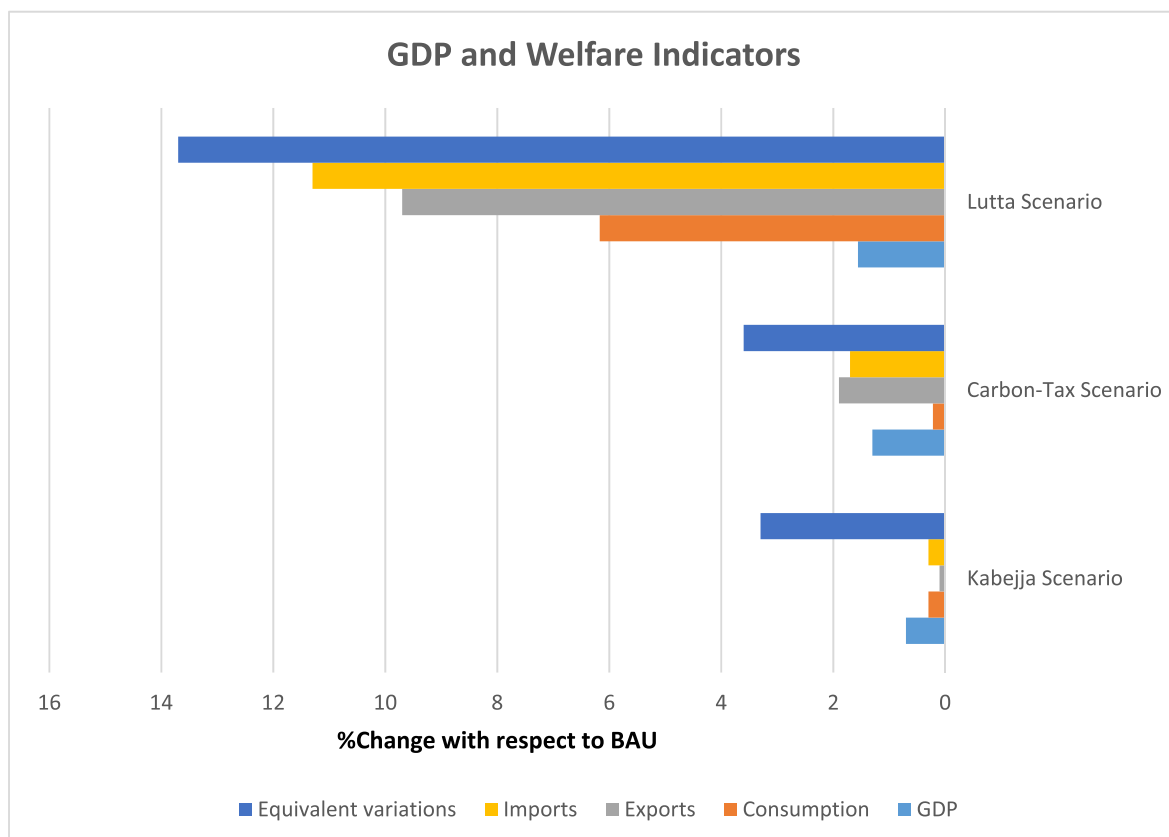


Fig. 5. Deviation of real GDP from the baseline conditions.

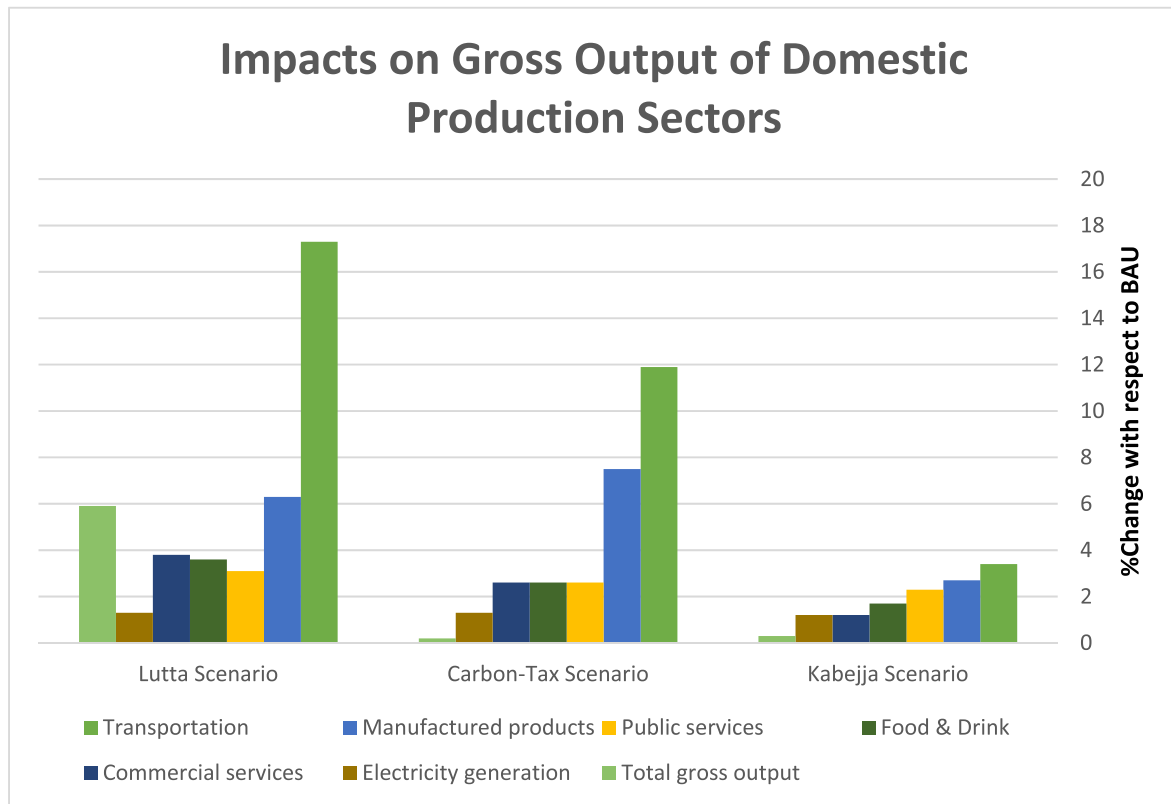


Fig. 6. Impacts of gross output on domestic production sectors.

3.2.4. Impacts of gross value added (capital and labor) on production sectors

The gross value-added increases in all scenarios compared to

baseline conditions (Fig. 7), mostly in transportation (Kabejja:3.2%; Carbon Tax:10.5%; Lutta:16.1%). This result suggests that the metropolitan should invest in the labor-intensive transportation sector for

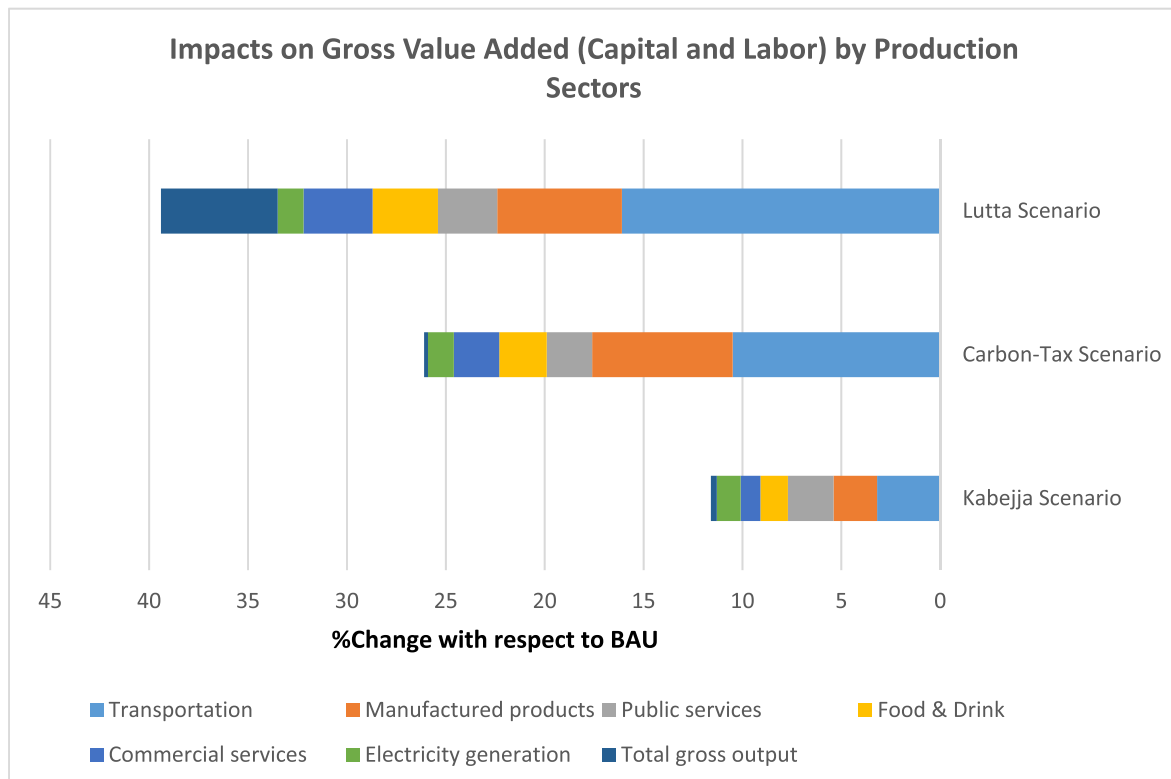


Fig. 7. Macroeconomic effects on Gross Value Added in 2050.

sustainable economic development. Compared to BAU, the need to inject more capital into transportation, commercial services, and manufactured products increases as you move towards Lutta. The capital requirement in low-carbon electricity generation in all scenarios remains stable, reaffirming the strategic objective of increasing low-carbon electricity in the energy balance for sustainability. This result emphasizes more, an additional requirement for extra capital investment, preferably from FDI, that would result in increased GDP and employment opportunities. Sustainability is plausible if the metropolitan adopts the Lutta scenario.

3.2.5. Sensitivity analyses

Because the elasticities of substitution values are sourced from literature, there is always uncertainty about simulation results in a CGE model. Therefore, we have employed an unconditional, systematic sensitivity analysis for these values following [145]. This was done to check for the robustness of the simulation results and any possible perturbation in these constant elasticities of substitution values that might arise.

Sensitivity analysis was carried out on the values of elasticities of substitution for production inputs, intermediate inputs, and household consumption by varying their values by 10% in either direction to check for consistency of the model results. The analysis showed that the change in the value of the constant elasticities of substitution resulted in a small change (0.02%–0.06%) in the macroeconomic feedbacks. This indicates that the results given by this study would be consistent even if a variation of 10% in the values of the elasticities of substitution was to be made in the middle of the study period.

4. Conclusion and policy implications

The study assessed the macroeconomic effects of the low-carbon electrification of the GKMA energy policy on the economy of the metropolitan, a sub-Saharan emerging economy with a huge untapped PV-Solar power and less used hydropower potential. The study developed and used a single region, static GKMA-CGE model to examine the macroeconomic effects of this policy in four scenarios. Business as usual (BAU) is the baseline scenario and it depicts the current situation of GKMA’s energy management system with fewer commitments to a low carbon society by 2050. The other alternative scenarios, namely Kabejja, Carbon-Tax, and Lutta, are pathways where a low-carbon footprint for GKMA is highly emphasized. The results indicate GKMA would benefit economically with a GDP growth increase of Kabejja:0.7%; Carbon-Tax:1.3% and Lutta:1.56% as compared to BAU. The equivalent

variation (EV) in household welfare would increase by Kabejja:3.3%; Carbon-Tax:3.6% and Lutta:13.7% as compared to BAU. Energy intensity of GDP would decrease by Kabejja:1.1%; Carbon-Tax:1.48% and Lutta:7.8% as compared to BAU. GKMA economy would shift gradually towards Lutta with a significant decrease in the CO₂ emissions intensity of GDP of 60.6% as compared to BAU. It is feasible to implement the low-carbon electrification of the GKMA energy policy because the metropolitan is endowed with an abundant hydropower potential (2000 MW) and it is located astride the equator, having 5.1 kWh/m²/day of solar energy incident throughout the year. Implementing this policy would promote a clean environment, improve energy efficiency, increase employment within the metropolitan and also expand the economy. The study recommends adopting the Lutta scenario for sustainability.

The analysis and discussion of the GKMA-CGE model results presented in this paper support design of energy policies from a local to a global perspective by considering the key outcomes of this study as policy implications. For example, the 60.6% reduction in the CO₂ emissions intensity of GDP could be considered valuable in the struggle to keep at bay the cumulative global CO₂ emissions intensities that infringe on the restriction of the 2-degree centigrade global temperature rise target. However, to enhance and achieve this macroeconomic effect, a significant injection of FDI into the metropolitan capital factor is necessary as this is also expected to result in increased GDP, improved household welfare, and decrease in the energy intensity of GDP. And although the study focused on GKMA, the quantified macroeconomic effects offer valuable insights that apply to a global wider perspective. This could be achieved by benchmarking with similar economies that are located astride the equator amidst having abundant hydropower and/or any other new and renewable potentials such as geothermal for energy policy design.

This study focused majorly on the macroeconomic feedbacks of energy impacts in terms of sectoral output, equivalent variation (EV) in household welfare, the energy intensity of GDP, and the CO₂ emission intensity of GDP. Further studies on the low-carbon electrification of the GKMA energy policy in areas not covered in this study, such as; the effects of the much-needed FDI on household welfare are also necessary going forward.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

Mathematical Development of a CGE Model

Suppose a single-region static CGE model with a flow mechanism described using a mathematical structure. If we consider an economy of two industries producing a similar commodity in a perfectly competitive environment, with a representative household endowed with two factors of production, capital K and labor L, where labor is mobile across sectors and capital is sector-specific. Then the characteristic behavior of the production firm’s technology in each sector would be described by the Cobb-Douglas production function as;

$$1) X_i = A_i L_i^{\delta_i} K_i^{(1-\delta_i)}$$

where X_i, L_i, K_i represent respectively output, labor demand and capital demand, for industry i and A_i, δ_i are parameters.

Index i represents the set of industries in the economy.

$$i \in I = \{bns, ser\}$$

The demand for the factors of production given the unitary cost of labor w and that of capital r_i , for which the price of output P_i are expressed in terms of the profit maximization of the production firm as;

$$\pi_i = P_i X_i - w L_i - r_i K_i$$

Applying the Cobb-Douglas technology function gives the profit maximization as:

$$\pi_i = P_i A_i L D_i^{\alpha_i} K D_i^{(1-\alpha_i)} - w L D_i - r_i K D_i$$

So that the first-order conditions become:

$$\frac{\partial \pi_i}{\partial L D_i} = P_i A_i \alpha_i L D_i^{\alpha_i-1} K D_i^{(1-\alpha_i)} - w = 0$$

$$\Rightarrow \frac{\alpha_i P_i X_i}{L D_i} = w$$

$$\Rightarrow 2) L D_i = \frac{\alpha_i P_i X_i}{w}$$

$$\frac{\partial \pi_i}{\partial K D_i} = P_i A_i (1 - \alpha_i) L D_i^{\alpha_i} K D_i^{(1-\alpha_i)-1} - r_i = 0$$

$$\Rightarrow \frac{(1 - \alpha_i) P_i X_i}{K D_i} = r_i$$

$$\Rightarrow 3) K D_i = \frac{(1 - \alpha_i) P_i X_i}{r_i}$$

Interestingly from the demand equations 2) and 3)

$$2) L D_i = \frac{\alpha_i P_i X_i}{w} \quad 3) K D_i = \frac{(1 - \alpha_i) P_i X_i}{r_i}$$

We can therefore deduce:

$$(a) P_i X_i = w L D_i + r_i K D_i$$

But household income depends on factor endowment from labor and capital thus;

$$4) Y = \sum_i (w L D_i + r_i K D_i)$$

The income generated is entirely dedicated to the consumption of goods and services. The consumption (Utility) depends on household preferences represented as;

$$5) U = B C_{bns}^{\beta} C_{ser}^{1-\beta}$$

Suppose that these preferences are represented by a Cobb-Douglas utility function then, Utility maximization subject to the budget constraint will determine the demand functions for both commodities, therefore;

$$Max U = B C_{bns}^{\beta} C_{ser}^{1-\beta} \quad s.t \quad Y = \sum_i P_i C_i$$

And the Lagrangian being:

$$\Gamma = B C_{bns}^{\beta} C_{ser}^{1-\beta} + \lambda \left(Y - \sum_i P_i C_i \right)$$

So that the first-order conditions become:

$$(i) \frac{\partial \Gamma}{\partial C_{bns}} = \beta B C_{bns}^{\beta-1} C_{ser}^{1-\beta} - \lambda P_{bns} = 0 \Rightarrow \lambda = \frac{\beta U}{P_{bns} C_{bns}}$$

$$(ii) \frac{\partial \Gamma}{\partial C_{ser}} = (1 - \beta) B C_{bns}^{\beta} C_{ser}^{1-\beta-1} - \lambda P_{ser} = 0 \Rightarrow \lambda = \frac{(1 - \beta) U}{P_{ser} C_{ser}}$$

$$(iii) \Rightarrow Y = \sum_i P_i C_i = P_{bns} C_{bns} + P_{ser} C_{ser}$$

From the first order conditions we get:

$$\lambda = \frac{\beta U}{P_{bns} C_{bns}} = \frac{(1 - \beta) U}{P_{ser} C_{ser}} \Rightarrow P_{ser} C_{ser} = \frac{(1 - \beta) P_{bns} C_{bns}}{\beta}$$

From the budget constraint, we get:

$$(a) Y = P_{bns} C_{bns} + \frac{(1 - \beta) P_{bns} C_{bns}}{\beta} \text{ from which we obtain the demand function as:}$$

$$6) C_{bns} = \frac{\beta Y}{P_{bns}}$$

Applying a similar method, the demand function for the other commodity can be expressed in the same way as.

$$7) C_{ser} = \frac{(1 - \beta) Y}{P_{ser}}$$

From equations (6) and (7)

$$6) C_{bns} = \frac{\beta Y}{P_{bns}} \quad 7) C_{ser} = \frac{(1-\beta)Y}{P_{ser}}$$

We can then deduce that:

$$(b) Y = \sum_i P_i C_i$$

Equilibrium between supply and demand on the markets for goods and services determines the price of each commodity, thus;

$$8) X_i = C_i$$

Equilibrium between supply and demand on the markets for factors of production determines the price of each factor, so that;

$$9) \overline{L S}_i = \sum_i L D_i$$

$$10) \overline{K S}_i = K D_i$$

Therefore, this scenario generates 6 endogenous variables from 6 equations.

$$1) X_i = A_i L D_i^{\alpha_i} K D_i^{(1-\alpha_i)} = 2 \text{ equations}/2 \text{ variables} = X_i$$

$$2) L D_i = \frac{\alpha_i P_i X_i}{w} = 2 \text{ equations}/2 \text{ variables} = L D_i$$

$$3) K D_i = \frac{(1-\alpha_i) P_i X_i}{r_i} = 2 \text{ equations}/2 \text{ variables} = K D_i$$

With 4 equations for household that define the corresponding 4 variables:

$$4) Y = \sum_i (w L D_i + r_i K D_i) = 1 \text{ equation}/1 \text{ variable} = Y$$

$$5) U = B C_{bns}^{\beta} C_{ser}^{1-\beta} = 1 \text{ equation}/1 \text{ variable} = U$$

$$6) C_{bns} = \frac{\beta Y}{P_{bns}} = 1 \text{ equation}/1 \text{ variable} = C_{bns}$$

$$7) C_{ser} = \frac{(1-\beta)Y}{P_{ser}} = 1 \text{ equation}/1 \text{ variable} = C_{ser}$$

And 5 equations for the equilibrium conditions defining the 5 prices:

$$8) X_i = C_i = 2 \text{ equations}/2 \text{ variables} = P_i$$

$$9) \overline{L S}_i = \sum_i L D_i = 1 \text{ equation}/1 \text{ variable} = w$$

$$10) \overline{K S}_i = K D_i = 2 \text{ equations}/2 \text{ variables} = r_i$$

Therefore, a total of 15 equations and 15 endogenous variables are generated for modeling this scenario with only exogenous variables shockable during the simulation. But these equations are not independent requiring the application of the Walras' law. Using equations 6) and 7):

$$6) C_{bns} = \frac{\beta Y}{P_{bns}} \quad 7) C_{ser} = \frac{(1-\beta)Y}{P_{ser}}$$

We get:

$$P_{bns} C_{bns} + P_{ser} C_{ser} = \beta Y + (1-\beta)Y$$

So that:

$$P_{bns} C_{bns} + P_{ser} C_{ser} = Y$$

Replacing Y using equation 4) from above:

$$4) Y = \sum_i (w L D_i + r_i K D_i)$$

We can state:

$$P_{bns} C_{bns} + P_{ser} C_{ser} = \sum_i (w L D_i + r_i K D_i)$$

From equations 2) and 3) previously we have:

$$2) L D_i = \frac{\alpha_i P_i X_i}{w} \quad 3) K D_i = \frac{(1-\alpha_i) P_i X_i}{r_i}$$

Using these equations, the right-hand side of our expression becomes:

$$P_{bns}C_{bns} + P_{ser}C_{ser} = \sum_i \left(w \frac{\alpha_i P_i X_i}{w} + r_i \frac{(1 - \alpha_i) P_i X_i}{r_i} \right)$$

Thus:

$$P_{bns}C_{bns} + P_{ser}C_{ser} = \sum_i P_i X_i = P_{bns}X_{bns} + P_{ser}X_{ser}$$

And;

$$P_{bns}C_{bns} + P_{ser}C_{ser} = P_{bns}X_{bns} + P_{ser}X_{ser}$$

Assuming that the market for *bns* and *ser* is balanced, so that:

$$X_{bns} = C_{bns}$$

then:

$$P_{bns}X_{bns} + P_{ser}C_{ser} = P_{bns}X_{bns} + P_{ser}X_{ser}$$

And:

$$P_{ser}C_{ser} = P_{ser}X_{ser} \Rightarrow C_{ser} = X_{ser}$$

A CGE framework assembles economic data to a set of mathematical equations similar to these, capturing the production and consumption structures as well as the income flows to capture the structure of the economy and behavioral response of agents [58].

Table T1
Aggregated GKMA-SAM of the baseline year 2015 (US\$ millions)

		Expenditure									
		Production		Factors		Institutions		Capital accounts	Rest of the world	Total	
		Activities	Commodities	Labor	Capital	Household	Government				
Receipt	Activities		23,486							23,486	
	Commodities	4,100				12,560	2,816	7,728	902	28,106	
	Factors	Labor	5,270								5,270
		Capital	10,430								10,430
	Institutions	Household			5,270	10,430		1,258		5,318	22,276
		Government	1,496	1,870			2,143			28	5,537
	Capital Account					7,500	213		15	7,728	
	Rest of the world	2,190	2,750			73	1,250			6,263	
Total	23,486	28,106	5,270		22,276	5,537	7,728	6,263			

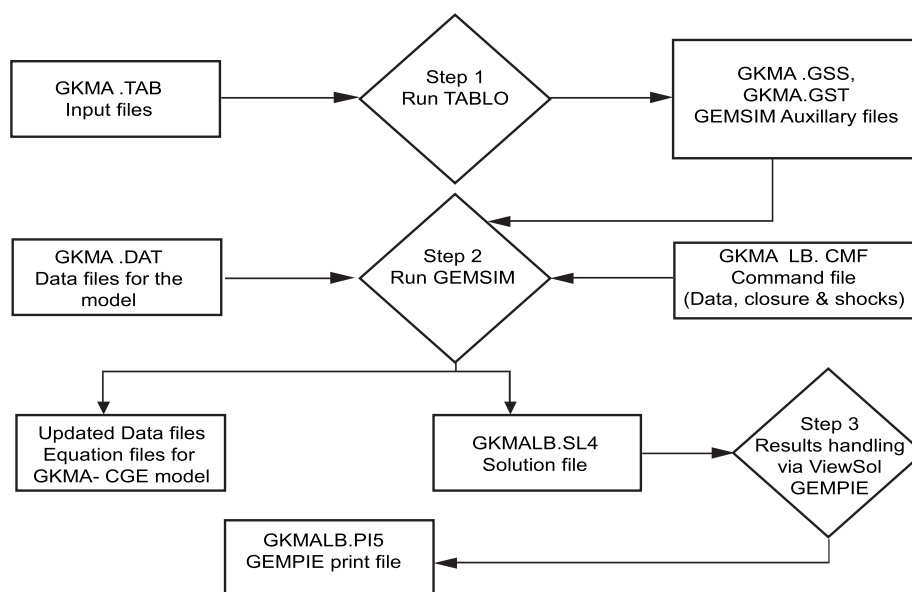


Fig. F1. GKMA – CGE Model Simulation

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