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Review article

A sustainable energy portfolio for Greater Kampala Metropolitan Area towards the mid-century

Ismail Kimuli *, Michael Lubwama, John Bosco Kirabira, Adam Sebbit

Mechanical Engineering Department, CEDAT, Makerere University Kampala, Uganda

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ABSTRACT

With steadfast economic development, the Greater Kampala Metropolitan Area (GKMA) faces increasing pressures to raise low-carbon electricity in the energy consumption by fuel type, abate CO_2 emissions, and also restructure transportation for sustainability. GKMA is Uganda's capital with rampant anthropogenic interference that causes climate change. A sustainable energy portfolio is a low-carbon scenario endowed with CO_2 emissions abatement strategies for GKMA towards 2050. Using TIMES-VEDA to address the knowledge gap, the study develops and examines a sustainable energy portfolio for GKMA. TIMES-VEDA is an engineering model generator with a bottom-up approach, paying in-depth attention to low-carbon themes while optimizing energy management systems. The analysis shows that sustainability is plausible by optimizing the total primary energy supply, electrical power production from PV-solar & hydropower technologies, and switching 90% of passengers of the road category to the Kampala metro.

1. Introduction

Greater Kampala Metropolitan Area (GKMA) is the social, political, industrial and commercial hub of Uganda, with a 3.1% population growth and 5.8% GDP growth (KCCA, 2014). Its supply energy comprises hydropower, biomass at 90%, solar, peat, and fossil fuels. The potential for hydropower production is 2,000 MW and that of solar energy is 5.1 kWh/m^2 daily throughout the year yet the petroleum oils are 100% imported through Mombasa, Kenya (MEMD, 2015b).

Despite this economic growth, the metropolitan still faces insufficient electricity in the energy balance, a non-optimized primary supply mix, a notorious haze resulting from industrial combustion and uncontrolled petroleum used in the transport sector, and unquantified & unabated CO_2 emissions from other energy activities that support economic development, making the GKMA energy system unsustainable (MEMD, 2015b). The GKMA (Figure 1) has traditionally relied on biomass for heating and fossil fuels for transportation demand. But over dependency on biomass for heating and fossil fuels for transportation is unsustainable because biomass harnessing results into deforestation and carbon emissions into the troposphere, whereas fossil fuels emit large volumes of CO_2 that cause global warming. The use of electricity as a primary source for heating is understood to be sustainable because electrical power production from low-carbon technologies is plausible in the GKMA. This study develops and examines a sustainable energy portfolio for the GKMA as a reasonable countermeasure to these challenges.

Sustainability has been elucidated in various ways in the literature. However, this study considers sustainability as that practice for which the global energy demand for economic growth considers the use of new and renewable energy resources in a way that their replenishment is faster than the consumption rate (Oyedepo, 2012; Quispe et al., 2017; Xie et al., 2020; Ahmad et al., 2020; Ulucak and Ozcan, 2020); the CO_2 emissions that cause a notorious haze enter the atmosphere slower than the pace they are recycled or rendered harmless (Fan et al., 2020; Sharma et al., 2020; Habert et al., 2020); the world population growth rate rhymes the GDP growth rate (Adams et al., 2020; Tapsoba et al., 2020); deficiency in human needs and starvation in the remote areas of the world is at an absolute minimum (Yang et al., 2020; Lajoie-O'Malley et al., 2020); and that there is true enduring democracy for all humanity (Nerubasska et al., 2020).

Therefore, in light of sustainability, hydropower and solar energy have been proven to be major supplies in the sustainable renewable mix, and their optimization in the global primary energy is considered essential to the United Nations' SDG7 (Büyüközkan et al., 2018; Ioannidis et al., 2019; Bogdanov et al., 2021). Hydropower technologies are fundamental in the realization of the SDG-7 goal (Yetano Roche et al., 2020; Caster et al., 2020; Elavarasan et al., 2020; Eras-Almeida et al.,

* Corresponding author.
E-mail address: 73kimuli.ug@gmail.com (I. Kimuli).

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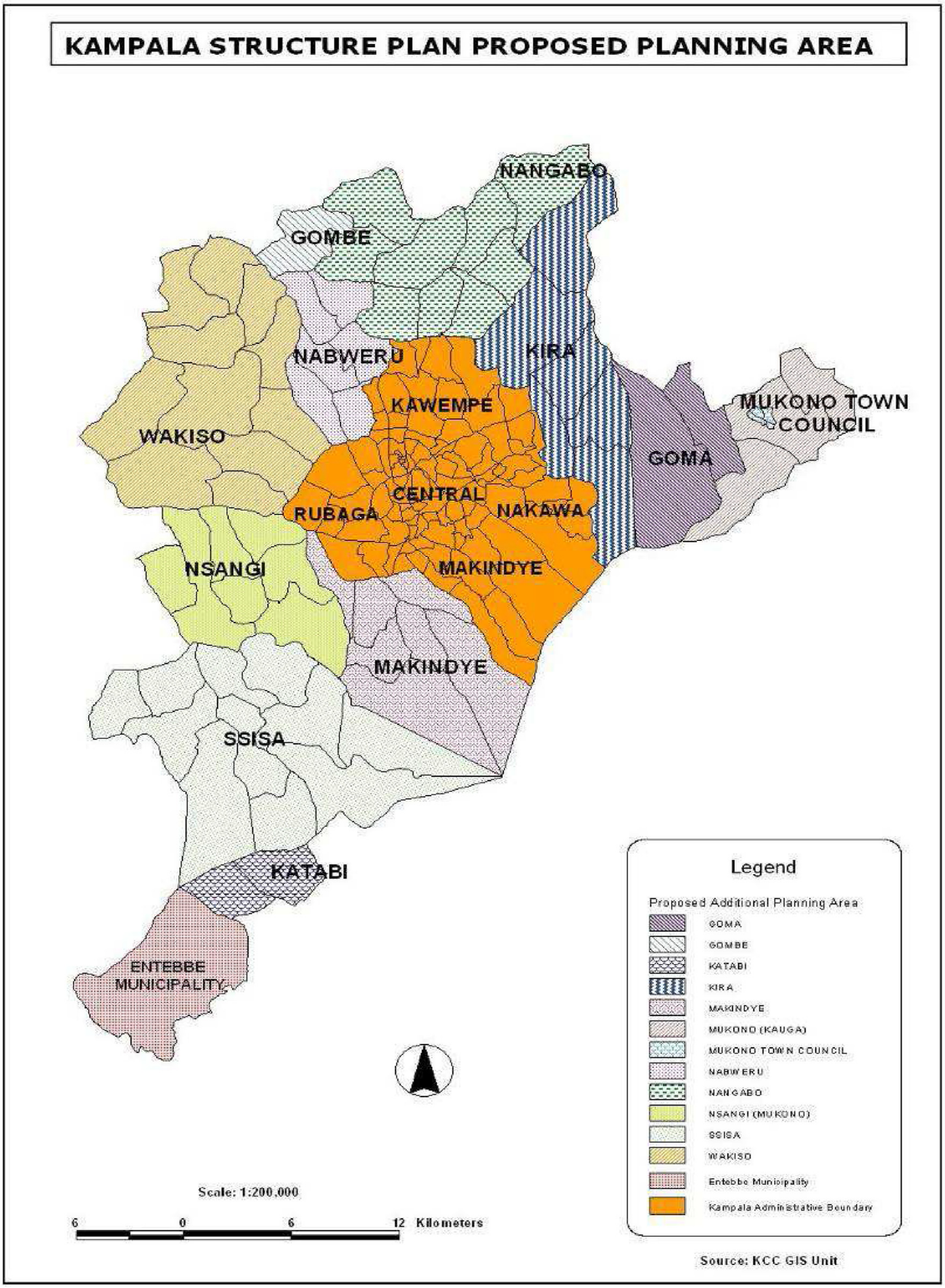

Figure 1. Map showing GKMA geographical planning area.

2020). And this is because when appropriately designed and applied, hydropower is an affordable, reliable, and sustainable electrical power production technology with near-zero carbon emissions to the atmosphere (Siri et al., 2020; Yoosef Doost et al., 2020; Majid, 2020). Hydropower is useful in freshwater management, climate mitigation & adaptation services, and also a dependable energy storage technology (Rehman et al., 2015; Nikolaou et al., 2020; Groppi et al., 2021).

However, with the present-day advancement and progress in PV-solar technologies, economies located astride the equator can sustainably rely on PV-solar energy for future electricity demand (Ahmed et al., 2020; Adenle, 2020). The use of advanced solar technologies in the primary supply mix is considered a key driver for abating global CO_2 emissions and balancing the energy-environmental-economic fabric, making it an important resource in achieving the SDG-7 goal. Therefore, the sustainable energy portfolio for the Greater Kampala Metropolitan Area relies heavily on hydropower and PV-solar technologies for electrical power production because hydropower & solar energy are abundant in the GKMA, and their presence in the energy mix promotes SDG7.

There is overwhelming evidence that the accumulation of carbon emissions in the troposphere causes a notorious haze and also contributes to climate change (Xu et al., 2016). Despite these scientific facts, CO_2 emissions into the earth's atmosphere continue to accumulate mainly from the utilization of energy resources. Although this phenomenon has been scientifically investigated and verified, there is still some degree of uncertainty about the magnitude of its impact at a metropolitan level in a sub-Saharan developing economy. This will continue in the foreseeable future, although global mechanisms for CO_2 emissions abatement, such as the Paris Low-carbon Roadmap, are still in effect with a significant number of signatories. The SDG 7 and SDG 11 if properly adhered to, could sufficiently address these challenges. Therefore, coveted efforts at individual local levels are necessary to uphold SDG7 & SDG11, and this study proposes such initiatives through the development and analysis of a sustainable energy portfolio for the GKMA towards 2050.

The authors transform the immediate energy management challenges of the GKMA into the main objective and three specific objectives to guide the research work. The main objective of this study is, therefore, to develop a framework for the evaluation of the energy impacts of the GKMA sustainable energy portfolio with the following specific objectives; (1) To develop a low-carbon energy scenario for the GKMA. (2) To develop an energy model that assesses the energy impacts of the low-carbon scenario on the GKMA energy system. (3) To evaluate the policy significance of the quantified impacts of the low-carbon scenario. There are a few studies that tackle the urgent energy challenges of the GKMA, and those studies have only considered economy wide effects of the energy management system, such as deviation from actual GDP and equivalent variation in household income due to the implementation of suggested policy shifts (Kemausuor et al., 2018; Daniel and Kim, 2022). Such studies did not consider the energy impacts of a sustainable energy portfolio of GKMA towards the mid-century. Therefore, there is a knowledge gap concerning the primary supply energy, electrical power production by fuel type, energy consumption by fuel type and by sector, carbon emissions by fuel type, and the system cost of the sustainable energy portfolio of the GKMA towards the mid-century. The study uses the TIMES-VEDA modeling framework, a bottom-up approach, to address the knowledge gap. For this purpose, therefore, the TIMES-VEDA analysis was helpful in answering the following research questions: (a) What new and renewable energy resources in the vicinity of the GKMA can be used for the development of a sustainable energy portfolio? (b) How can the variety of the supply energy be optimized so that the GKMA achieves a sustainable energy portfolio by mid-century? (c) How does the opted array of technologies affect the development of the GKMA energy portfolio? (d) What is the most appropriate carbon mitigation plan for the Greater Kampala Metropolitan Area?

Based on the preceding background, the authors define a sustainable energy portfolio for the GKMA towards 2050 as a low-carbon energy scenario or pathway created using a distinct scenario development methodology and quantitatively analyzed using TIMES-VEDA, an energy modeling framework (Aryanpur et al., 2019). It presents GKMA as a sustainable metropolitan towards the mid-century. It is developed using the methodology that was suggested by the United Kingdom Foresight Program on the Environmental Future and quantitatively analyzed using TIMES-VEDA, a bottom-up model generator (Berkhout et al., 2002; Saritas and Oner, 2004; Duinker and Greig, 2007; UK, 2008; Mahmoud et al., 2009). TIMES-VEDA is a bottom-up energy model generator endowed with a variety of technologies arrayed in a reference energy management system (RES) over the planning horizon. TIMES-VEDA is data-intensive, demand-driven, multi-period, linear programming framework using exogenously determined demand projections with policy constraints to meet the demand at the least cost (Chiodi et al., 2013; Yeomans, 2017). The authors use TIMES-VEDA in this research work because of its in-depth consideration of low-carbon themes when optimizing the energy management system. TIMES-VEDA has been used over the years to develop sustainable energy management systems; for example (1) Wahyu Purwanto (2021) used a TIMES-VEDA modeling framework to plan the Indonesian fuel system by considering the minimum energy system cost up to the mid-century. During his analysis, it was established that provided the Indonesian government adopts the EURO diesel fuel specification with adjustment, the consumption of biofuels reduces diesel and gasoline by 79% and 19% in the energy system and also carbon intensity by 78% and 27%, respectively. (2), Al Jandal and Al Sayegh (2015) used a TIMES-VEDA modeling framework to determine the Kuwait Clean Energy Policy Options using Plausible Development Scenarios. During their analysis, it was established that renewable energies will deliver a fuel-saving and carbon emission abatement to fossil technology. (3) Bohra and Shah (2020) used an Optimization Modeling framework to mitigate carbon emissions in the future Qatar energy management system. Their study findings show that liquefied natural gas is a non-sustainable export going forward, but it is plausible to switch it with hydrogen fuel-cells harnessed during the reforming of natural gas for a post-carbon Qatar. Following a similar methodology, this study develops and makes an initial use of the GKMA-TIMES model to establish a Sustainable Energy Portfolio for the Greater Kampala Metropolitan Area. The development of the RES of the GKMA-TIMES model is the novelty of this study. This is because the impacts of energy systems that arise from energy modeling are region-specific due to variations in the GDP, population, and accessibility to the energy supply (Zhou et al., 2014; Wilkerson et al., 2015; Glynn et al., 2015; Debnath and Mourshed, 2018). The quantification and analysis of the impacts of the sustainable energy portfolio of GKMA are necessary because there is still some degree of uncertainty about the magnitude of their effects on a sustainable future and on the global efforts that abate carbon emissions.

Scenarios have been used in previous studies such as the Climate Change Emissions Scenarios of IPCC (Nakicenovic and Swart, 2000), Visions for a sustainable Europe (Rotmans et al., 2000), Bridging the gap between socio-economic storylines and energy modeling (Fortes et al., 2015), exploring alternative energy pathways in California (Ghanadan and Koomey, 2005), The development of strategies for renewable energy in Germany (Pregger et al., 2003), universal access to modern electricity by 2030 for sub-Saharan Africa (Bazilian M. et al., 2012), analysis of the Energy Demand for China in 2030 (SHAN et al., 2012), analysis of a sustainable energy scenario for the USA for the year 2050 (Tonn et al., 2010) and many other studies. Therefore, the development and evaluation of a sustainable energy portfolio for GKMA towards the mid-century follows a similar paradigm.

The motivation for this study is the necessity to establish a focused energy policy framework that addresses the immediate energy management challenges of the GKMA. The study considers the progression of the United Nation's SDG-7 & SDG-11 and the Paris Low-carbon Roadmap that tackles climate change. The Paris Low-carbon Roadmap promotes the use of energy resources in a manner that constrains global warming to a 2° temperature rise by 2100 (Grubler et al., 2018; Mittal et al., 2018; Gahlawat and Lakra, 2020). This study considers substantive carbon abatement majorly in electrical power production and transportation activities in that regard (Wang et al., 2018; Fujimori et al., 2014; Wang and Cheng, 2019; Zhang et al., 2020).

2. Literature review

A systematic review of existing literature on Uganda and the GMKA energy policy framework was carried out to validate the research gap, and the following are the key salient outcomes.

2.1. Uganda energy policy framework

Uganda's energy policy framework consists of the constitution of Uganda, the national development plan, public energy management institutions, development partners, and enacted Acts and policies.

2.1.1. Uganda's constitution

The Constitution of Uganda is the supreme law of the land that provides energy as public property. The access and utilization of this natural resource by Ugandans is a right that should be recognized and protected at any cost (UgGov, 1995).

2.1.2. National development plan I & II

The National Development Plan I&II contains the Uganda Vision 2040, proposing electrification of the country to 80% by 2040, contrary to the current 1.4% electrification. Its main objective is to raise electrical power in the energy balance for economic development. This will be achieved by production of more low-carbon electricity, electrification of rural areas, use of advanced technologies for energy efficiency, mitigating losses in the electricity transmission and distribution systems, making revisions in the existing policy framework, and promoting sustainable biomass harnessing (NPA, 2007; NPA, 2010). It suggests that a public-private partnership (PPP) framework enhances efficiency in the energy sector. However, mechanisms that underpin such improvements are not discussed. Such as the energy impacts and macroeconomic effects that might arise from the proposed measures. GKMA, as the country's capital, is not mentioned in the NDP. Therefore, NDP doesn't offer a suitable readdress of the immediate energy challenges for the GKMA, such as increasing low-carbon electricity in the energy balance, optimization of the primary energy, and CO_2 emissions abatement strategies for sustainability.

2.1.3. Institutions for public energy management

Uganda's energy policy framework is managed by the Ministry of Energy and Mineral Development (MEMD), Rural Electrification Agency (REA), and Electricity Regulatory Authority (ERA). The MEMD is the overseer of all aspects pertaining to energy supply and consumption in Uganda. It formulates and drives the energy policy framework in Uganda. REA operationalizes the rural electrification program. ERA release permits for electricity production and sales (MEMD, 2014). However, these public institutions do not have structures at the metropolitan level and thus don't cater for the immediate energy management concerns of the GKMA.

2.1.4. Energy Acts and Policies in Uganda

The Uganda energy policy framework comprises numerous energy Acts and Policies. These Acts and Policies include the Electricity Act, 1999; The Energy Policy for Uganda, 2002; Renewable Energy Policy for Uganda, 2007 (GoU, 2007); the Atomic Act, 2008 (GoU, 2008); the KCC Strategic Plan; and the KPDP. The vital salient issues in this policy framework are listed in Table 1.

2.2. Total primary energy supply

Uganda's supply energy includes hydropower, biomass (90%), solar, geothermal, peat, and fossil fuels (MEMD, 2015a). GKMA has approximately 2,000 MW of hydropower along the White Nile, a justifiable fifty mnts of biomass annually, and 5.1 kWh/m^2 everyday of solar energy is available all year (Bahati et al., 2010; Herman et al., 2014).

The use of biomass is associated with unquantified and unabated CO_2 emissions into the troposphere and a substantial deforestation (MEMD, 2015a). Charcoal is the main source of energy for heating in the country. Combustion of charcoal is done on a metallic stove called a SIGIRI but the use of a clay stove is picking up (Basu et al., 2013; Okello et al., 2013; Chen et al., 2012; Pandey et al., 2007).

Table 1. Energy acts and policies in Uganda.

SN	Act or policy	Key features	Observations/gaps in the context of GKMA
1.	The Electricity Act, 1999	• To tackle the electricity sector disputes. • To regulate the electricity sector • To establish the Rural Electrification Fund (REF) that enhances electricity availability in the rural areas.	• The act does not; o Tackle the optimization of the fuel mix during power generation o Provide a suitable link of the power sector with other economic sectors o Examine the energy impacts of the suggested policy shifts. o Provide a sustainable energy portfolio for the GKMA.
2.	The Energy Policy for Uganda, 2002	• Uganda has a vast supply energy mix dominated by biomass, Solar, and hydropower. • Electricity is available to a few in the metropolitan areas. • Inefficient electricity in the energy balance. • A need to attract foreign direct investment (FDI) to improve service delivery. • Transformation of downstream petroleum industry (GoU, 2002).	• The inability of the Government to do research and development because of the: o Absence of appropriate key personnel; o Budget shortfalls; and o The absence of a suitable curriculum in the country's education system. • Unoptimized supply energy • Lack of appropriate communication among the stakeholders. • The failure by the government to devise mechanisms to deliver electricity to the rural poor (GoU, 2002). **However, in line with GKMA;** • The policy doesn't discuss the implementation of its objectives at the GKMA level. • The energy policy of Uganda doesn't explicitly mention GKMA and thus doesn't provide an adequate readdress of its immediate energy management challenges.
3	Renewable Energy Policy for Uganda, 2007 (GoU, 2007)	• Advocating the enhancement of renewable energies • To promote suitable technology transfer in renewable energy technologies; • Enhance efficiency in the biomass industry • To promote sustainable practices for biofuels production • To establish modalities of tapping into the municipal and industrial waste to generate sustainable energy	• The energy impacts arising from harnessing of the municipal waste are not well elucidated. • The policy doesn't mention GKMA and thus does not provide an appropriate attention to GKMA immediate energy challenges. • The need to increase low-carbon electrification in the energy balance is not mentioned
4	The Atomic Act, 2008 (GoU, 2008)	• To provide electricity from ionizing radiation • To set up the Atomic Energy Council (AEC);	• The use of Uranium for civilian electricity is yet to commence in Uganda. The delay is due to the

(continued on next page)

Table 1 (*continued*)

SN	Act or policy	Key features	Observations/gaps in the context of GKMA
		• Provide mechanisms for a safer harnessing of ionizing radiation; • Provide modalities to comply with international safety standards for harnessing ionizing radiation	associated global political and security concerns. • However, the act is silent on GKMA and thus doesn't provide a satisfactory readdress of its immediate energy management challenges.
5	KCCA Strategic Plan 2014–2019	• Provides sustainable development • Proposes a cohesive Transportation system • Proposes a robust Health and Educational infrastructures • Proposes a modern and efficient management and governance system	• The plan doesn't provide a detailed mechanism for addressing global warming and climate change. • The plan does not provide a suitable linkage between the energy sector and other economic sectors for tracing economic progress. • The strategy for street lighting using PV-solar technologies is not clear. There is no analysis for future energy impacts arising from this initiative. • This plan doesn't offer a focused energy policy framework for the GKMA.
6	The Kampala Physical Development Plan, KPDP	• Gazettes the GKMA's new boundaries and provides the maps. • Provides the new physical and spatial planning for the Greater Kampala Metropolitan Area (KCCA, 2014).	• GKMA has a population of 4.1 million and is projected to grow by 3.1% over the planning period with no focused energy policy in place • The KPDP doesn't address the urgent energy management challenges of the metropolitan.

2.3. Discussion on the current state of energy management for GKMA

Uganda's energy policy framework doesn't address the immediate energy management concerns of the GKMA. Therefore, a sustainable energy portfolio needs to be developed to address these challenges. Uganda's available energy supply translates into the available supply energy for the metropolitan over the planning period. Electrical power production is primarily hydro-based, and heating is predominantly done using woody biomass. Uganda and GKMA continue to rely on imported fuels from Kenya and Tanzania.

The absence of a focused energy plan is a barrier to the optimization of the supply energy for the GKMA. Available literature shows that advanced countries such as the United States of America, the European Union, the United Kingdom, and China continue to evaluate their energy portfolios with an aim of securing a justifiable future (Ericsson et al., 2004; Tsai and Chou, 2004; Wang, 2004; Winkler, 2005). Similarly, emerging economies such as the Asian tigers with efficient energy portfolios also continue examining their frameworks with a similar objective of sustainable economic development (Abdullah, 2005; Karki et al., 2005; Lebel et al., 2002). This study, therefore, follows similar practices by developing a sustainable energy portfolio for GKMA towards the mid-century to address its immediate energy challenges.

3. The low-carbon scenario

The evolution to an energy portfolio that accounts for the richness in the hydropower & PV-solar-based renewable energy resources for low-carbon electricity generation was pivotal during this scenario's construction. This is because the metropolitan lies astride the equator with 5.1 kWh/m^2/day incident throughout the year yet in its amidst having an abundance of hydropower resources (Alobo and Xsabo, 2013). The crafted low-carbon scenario encompasses significant roles for both government and the public, each taking an increasingly vital role in achieving sustainable economic growth for the metropolitan. During the scenario's development, we envisioned a situation where great steps towards independent low-density settlements of the metropolitan area are realizable, a goal we hope is achievable for sustainability. We first present the overall concept of the low-carbon scenario before quantitative analysis of the energy portfolio is made.

It is assumed that by the year 2050, GKMA is hardly recognizable to those who lived in the year 2022. People living in upscale GKMA have comfortable households and are very social. Those that are living in less affluent, less-populated and independent eco-villages also rejoice though in fewer flamboyant behaviors compared to the upscale residents of the metropolitan. GKMA's lifestyle from the year 2022 was unjustifiable regarding every imaginable dimension, from electrical power to water resources, from the ecosystem of life to foodstuffs. Everyone is amazed currently that GKMA evaded a catastrophe but a thorough analysis of facts shows that the spectacular conversion to a low-carbon footprint started in 2022 during a sustainable energy portfolio development process. The small trading centers like Bwaise, Kabalagala, Kibuli, Kibuye, Makindye, Kansanga, Bunga, Bugolobi, Nansana, Kasangati, Wandegeya, Kira, Ntinda, Kawempe, Namasuba, Bunamwaya, Abayita Ababiri, Kajjansi, Seeta, Mukono town, Matugga, Kireka, Seeta, Naalya, Namugongo and Bweyogerere are extinct. They have metamorphosized into affluent suburbs with independent eco-villages and among those that were very close to Kampala City and Entebbe of 2022 have been transformed and are part of a Mega-City now called the Kampala Capital City (KCC). KCC and the immediate affluent suburbs which were part of the Wakiso, Mukono, and Kampala districts of 2022 now constitute the GKMA.

The residents in the sparsely populated areas of the GKMA in the year 2050 mainly rely on ICT gadgets for most of their economic activities. Thus, transportation demand is at an absolute minimum with respect to the year 2022. The poor road networks of Kabalagala, Bugolobi, Bwaise, Najjanankumbi, Sentema, Masanafu, Seeta, Konge, Busiza, Busabala, Nakawuka, Kawempe, Mulago, Kamwokya, Kisaasi, Kibuli, Kitezi, Namugongo, Sonde, and Mutundwe of the year 2022 are now pervious roads and driveways with new exotic names matching the current middle class. UMEME limited, the electricity utility management company, is now 100% a public enterprise with a fully automated management system. Every household is using a prepaid billing system locally known as YAKA and it is mobile phone enabled, making it easier to access the low-carbon electricity supply contrary to the year 2022. The parastatal that manages the water resources is still National Water and Sewerage Corporation (NWSC) and is 100% a government owned because of the associated security concerns. NWSC is fully automated with improved water quality and supply compared to the year 2022. NWSC management systems are environmentally compliant and highly automated with high-speed computers. The low-density settlements in the suburban areas of Buziga, Munyonyo, Entebbe Kitoro, Lukuli-Nanganda, Luzira-Biina, Bukasa-Muyenga, Seeta-Mukono, Sonde, Namugongo, Makindye, Bulange-Mengo-Lugala-Masanafu corridor, Kyengera-Nsanji, Bulenga and Maya, contrary to expectation, are blossoming with a dazzling scenery. This is because their residents formed well-organized eco-communities that conserve the environment. These suburban residential homes have kept outdoor grass compounds and comply with the existing organic waste management systems. The polyethylene bag, locally known as KAVERA was abolished a few decades ago, and all packing is done in organized disposable paper bags. GKMA residents are very organized and have community leaders locally known as BANAKYEWA~ the foremost, who oversee and protect the environment. The residents of GKMA are completely cosmopolitan, the youth are accustomed to dining at KFC, and McDonalds' outlets, and the elder people mostly dine at local food restaurants keeping less food at home.

Commercial and Residential Sectors: It is assumed that by the year 2050, all buildings in the commercial sector and households shall be equipped with closed-loop water systems, air-conditioned, using low-carbon electricity, having solar water heaters, piped gas systems, with various modern and efficient electrical appliances in residential buildings compared to their ancestors from the year 2022.

Transportation: It is assumed that by 2050, GKMA is a fully developed megacity that demands better life with advanced transportation systems dominated by public land passenger transportation. These systems are highly electrified and intelligent with the railway, road, and water transport of Lake Victoria, having many computer-controlled pedestrian walkways in the central business district of the KCC boundary from the year 2022. A visitor from the year 2022 is amazed to find KCC eerily quiet, having a modern Kampala metro system that is accessed via subways and electric commuter buses smoothly traversing the traffic-calmed streets. The Kampala Road, William Street, South Street, Luwum Street, Market Street, Arua Park Lane, Nakivubo Road, Kikubo Lane, Kiyembe Lane, Kiseka Market Lane, Nakasero Road, Buganda Road, Lumumba Avenue, Old Kampala Road, Acacia Avenue, Kitante Road, Nasser Road, Nkrumah Road and Nile Avenue of the year 2022 were transformed into pedestrian walkways with subways leading to the underground railway system of Kampala metro. GKMA invested heavily in a Kampala metro system, fly-overs, intelligent interchange junctions, and underpasses linking the populated areas of the metropolitan as a mitigation for traffic jams and congestion. The Clock-tower, the Yard, and Wandegeya junctions are a wonder to commuters of the year 2022. These three junctions were transformed into interchanges with subways leading to the main interchange of the Kampala metro system situated at the former Amber House on Kampala Road from the year 2022. The main interchange of the Kampala metro is typical of Gare du Nord in Paris, France. Some citizens still own cars though mainly of the hybrid type, but nearly all GKMA citizens travel using the municipal transportation dominated by the Kampala metro. These transportation systems are interlinked using high-speed computers clocking a benchmark score above 200 PFLOPS. The computers coordinate the Kampala metro, sedans, commuter buses, Boda-bodas, electric commuter buses, and pedestrian walkways as the city's inhabitants go about their daily business. The pedestrian walkways are typical of downtown Hangzhou City in Zhejiang Province of China.

CO_2 Emissions: It is assumed that the GKMA will uphold the SDG7 & SDG11, following a low-carbon development pathway to 2050. In 2050, despite the high-density settlements, the environment has near-zero carbon emissions. The transportation sector consumes fewer fossil fuels and uses more hydro and PV-solar based electricity. Global warming is no longer a sustainability challenge. Nearly all structures within GKMA have clay Mategula roof-tiles, with the major roads mostly pedestrian streets and walkways having canopy linings of KABAKANJAGALA a local forestry tree. The pedestrian lanes are keeping the environment free from CO_2 and the streets are cooler throughout the year.

4. Methodology

4.1. Scenario development

The energy portfolio was developed using an approach suggested by the United Kingdom Foresight Program on Environmental Future. Initially, five scenario drivers that could affect the GKMA energy management system were identified. Then an energy scenario was crafted by developing a rationally steady set of rules about these key drivers as a set of limitations for a strategic plan. Finally, this energy scenario was modeled with TIMES-VEDA for its energy impacts on the GKMA energy management system. The five scenario drivers are (1) Hydropower dependency, (2) Energy diversity, (3) Advanced technologies, (4) Socioeconomic factors, and (5) Carbon emissions. The five scenario drivers have three indicators; environment, energy, and socioeconomic indicators. The study focus on CO_2 emissions abatement is the environmental indicator and the main scenario driver of this study. The Energy indicator consists of the primary energy supply mix, technologies, and demand (Streimikiene et al., 2007; Dixit et al., 2010; Sovacool and Mukherjee, 2011). The socioeconomic indicators are GDP & growth rate, population & growth rate for each scenario (Riahi et al., 2007; Rout et al., 2011).

4.1.1. Hydropower dependency

There is an overwhelming urgency to control the over-dependency on hydropower for electricity generation because of its limited potential to meet future demand. We propose a scenario that diversifies the fuel for electricity generation away from hydropower dependency for electricity generation for sustainability. However, GKMA is currently depending on hydropower for electricity generation and for more years to come. Therefore, the dependency on hydropower becomes a key scenario driver in setting up the sustainable energy portfolio for GKMA towards 2050.

4.1.2. Energy diversity

The energy consumption in the metropolitan is projected to increase rapidly to meet economic development. The study considers the diversification of the supply energy away from over-dependency on biomass necessary for sustainability. This driver considers the other new and renewable energy sources in the primary mix, electricity generation, heating, and transportation. Energy diversity allows competition among fuels and technologies during the optimization of the supply energy.

4.1.3. Advanced technologies

The choice of energy technologies deployed is overriding in the development of sustainable energy portfolios (Demirbas, 2005; Asif and Muneer, 2007). Therefore, it is paramount to assess the energy technologies of the energy system of the GKMA when developing a sustainable energy portfolio. We assume that during scenario development, the consideration of advanced technologies, such as an electrified Kampala metro system, would have a profound effect on the sustainable energy portfolio of the metropolitan.

4.1.4. Socioeconomic factors

The attitude of the end-user and management, the existing energy policy framework, and the debate within academia on contemporary energy issues, such as a need for carbon abatement and global warming, will significantly affect the choice of a future sustainable energy portfolio. This study assumes that socioeconomic factors such as GDP, population growth, and accessibility to clean energy will influence the development of the sustainable energy portfolio.

4.1.5. Carbon emissions

Global warming due to unabated carbon emissions from the combustion of energy resources is now at the center of the global sustainability debate (Williams and Jackson, 2007; Boykoff and Boykoff, 2007). Uganda is among countries with the smallest per capita of carbon emissions. However, with the current economic development, CO_2 emissions are expected to grow rapidly in Uganda as GKMA urbanizes. Therefore, in light of global warming that results from human activities, GKMA's CO_2 emissions fronts a serious challenge to the worldwide abatement struggles.

4.1.6. Projections of the demand component

A comprehensive projection of the demand component for the low-carbon scenario over the planning horizon was done to provide an exogenous input to TIMES-VEDA. The projection of the end-use demands was carried out using an energy-economic elasticity model (Vaillancourt et al., 2017). Assumptions underpinning energy demand projections in this study are; Steady economic development, competition among primary supply fuels, and advanced technologies. The demand component was classed into commercial, residential, industrial, transportation and agriculture sectors. These were then presented to TIMES-VEDA as either activities or useful energy for modeling purposes.

4.2. Development of the GKMA-TIMES model

The GKMA-TIMES model was developed to examine the energy impacts of the sustainable energy portfolio towards 2050 in terms of the total primary energy supply, electricity generation by fuel type, energy demand by sector and fuel type, carbon emissions by sector and fuel type, and the total system cost as the objective function of the optimization process. TIMES-VEDA represents the energy system in form of a reference energy system (RES). It consists of VEDA Front-End (VFE) and VEDA Back-End (VBE) as management platforms of the model generator. VFE is for data handling and VBE is for results handling via dynamic users defined pivot tables.

TIMES-VEDA platform is composed of;

a The TIMES model source code, written in GAMS calculates for each region a total net present value (NPV) of an array of yearly expenses, that are bargain-based according to a modeler baseline year. These model expenses are then combined into a unitary price, which comprises the objective function that is minimized by the model in its balanced conditions. Concisely, TIMES is expressed as:

$$NPV = \sum_{r=1}^{R} \sum_{y \in YEARS} (1 + d_{r,y})^{REFYR-y} \times ANNCOST(r, y)$$

For which:

NPV is the objective function minimized during the modeling of the energy system; ***ANNCOST(r,y)*** the annual arrayed expenses per region r for year y and follows syntax inherent within GAMS; $d_{r,y}$ is the concession model rate; ***REFYR*** is the baseline year; ***YEARS*** the years defining the planning horizon.

R Regions considered in the model during the planning period.

b **VEDA user interface:** The VEDA interface comprises VFE and VBE. Exogenous data and assumptions are fed into VFE that provide input to the TIMES source code. The TIMES code uses a GAMS optimizer to output files that are read by VBE.

c **Solver**: calculates the set of simultaneous linear equations that are generated by the TIMES code at the least cost as reflected in the objective function.

d **Operating system**- Windows: This is the operating environment upon which all elements run (Loulou, 2008).

4.2.1. Model set-up

Foremost in evaluating an energy model, the appropriateness of the model detail, theory, methodology, and appropriateness of the geographical detail under study are determined. The model was set up as shown in Figure 2. The model data was assembled in flexible Excel workbooks that collectively comprised viable information employed in the design of the underlying RES. The GKMA-TIMES model comprises the Residential, Commercial, Industrial, Transport, and Agriculture demand sectors and an electrical power production module. The study uses 2015 as the base year and the analyses were performed using constant 2015-dollar prices. The model used the following units attributed to the technologies, processes, flows, and commodities:

- Monetary units are in 2015 US$;
- 2015 is the base year;
- Energy Carrier is in petajoules (PJ);
- End-use demand save for transport is petajoules (PJ);
- CO_2 emissions are in million tons of contained carbon (Mtn);
- Technology Activity save for Transport is petajoules (PJ);
- Passenger Transportation is in million-passenger-kilometer (mpk);
- Freight Transport Demand Technology Activity is million-tons-kilometer (mtk);
- Conversion Technology capacity is Gigawatts (GW);
- Process Technology capacity is petajoules/annum (PJ/a);
- Demand Technology Capacity save for transportation is petajoules/annum (PJ/a);
- Freight Transport Demand Technology capacity is million-tons-kilometer (mtk), and
- Electricity capacity GW.

4.2.2. Data considerations and assumptions

We develop the GKMA energy balance of the base year from the Uganda Energy Balance of 2015 for consistency with current Global data. The GKMA-TIMES database for energy processes and technologies

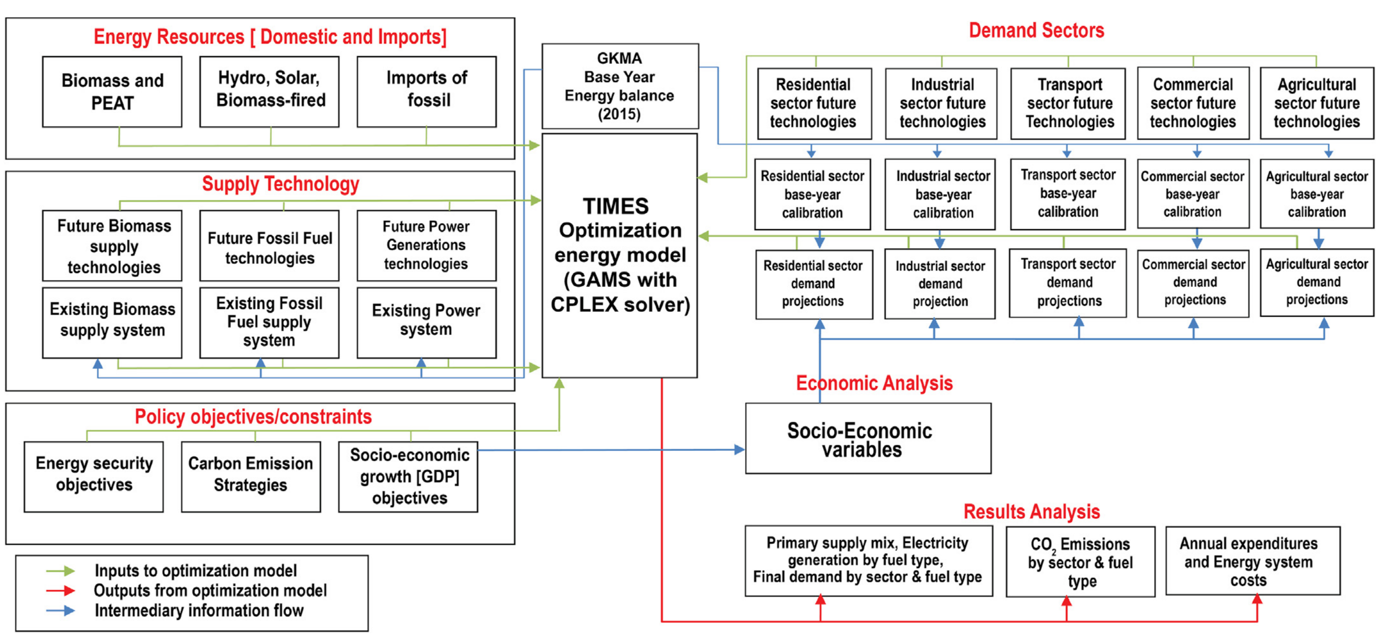

Figure 2. Energy portfolio modelling overview.

including associated CO_2 emissions coefficients follows the VEDA-TIMES model generator. In a few cases, separately referenced, the technology characteristics in the database were localized to meet specific GKMA data. During the study, we aligned the sustainable energy portfolio with GKMA's immediate concerns as stipulated in the Uganda Vision 2040. The analysis in TIMES-VEDA was performed using constant US $ 2015 prices.

4.2.3. The RES of the GKMA-TIMES model

The Reference Energy System (RES) was set up to show the arrangement of the GKMA-TIMES model by illustrating what constitutes an energy system. In a RES network diagram, processes or technologies are denoted as boxes, commodities appear as lines in a vertical plane and the commodity flows are denoted as horizontal links between the processes (boxes) and the commodities (vertical lines). Figure 3 represents the RES of the GKMA-TIMES model and the development of the RES for GKMA is the novelty of this study. The RES of the GKMA-TIMES model comprises the supply energy mix, electrical power production by fuel type, and all energy activities with their technologies and processes, from the primary to the final end-use energy demand.

4.2.4. Limitations of the TIMES-VEDA modeling framework

The bottom-up models such as TIMES-VEDA, represent the energy system from below by considering the entire energy system from the supply energy to the consumption in the various sectors, including all conversion phases. A hefty diversity of technologies, both on the primary supply and demand side, are fundamentally demonstrated with their economic, technological, and environmental considerations (Strachan and Kannan, 2008). In the TIMES-VEDA modeling framework, the energy system is represented as a RES. Given a well detailed array of technologies, the TIMES-VEDA modeling framework is a partial equilibrium model (Gabriel et al., 2001; Chiodi et al., 2013). The evaluation considers majorly the energy management system, while the economy-wide effects are not considered (Loulou, 2008). The greatest benefit of bottom-up modeling is its detailed representation of technologies.

Bottom-up models evaluate competition among technologies and they include the long-term trends in technology costs depending on their installed capacity using learning curves (Del Granado et al., 2018; Gargiulo and Gallachóir, 2013). During the evaluation process, the historical data is less emphasized, because its major use is the calibration of the base year of the baseline scenario of the model (Shen et al., 2021; Li et al., 2017). In this way, it is practicable to model technical innovations for CO_2 emission mitigation targets (Swan and Ugursal 2009; Lin et al., 2010; Yang et al., 2017; Shahbaz et al., 2020).

However, bottom-up models do exhibit critical drawbacks such as a) ignoring the policymaking behavior of various economic proxies, especially private households. They usually depend on fiscal indicators as the main policy variable for selection of appropriate technologies by assuming that technologies that deliver similar energy service act as perfect substitutes (Jaccard et al., 2003; Patt et al., 2010), b) They underestimate the elasticity of the energy system to respond to price signals or policy shocks leading to an overestimated cost of CO_2 emissions abatement strategy (Prina et al., 2021; Rehfeldt et al., 2020; Pavičević et al., 2020), c) they are data-intensive, often at a level of detail that is impractical in some economies such as GKMA.

However, top-down modeling frameworks such as the Computable General Equilibrium (CGE) models have potential in areas where bottom-up models like TIMES-VEDA are feeble, such as the inclusion of economy-wide impacts (Wing, 2006). But the Constant Elasticities of Substitution (CES) parameters that the modeler employs in setting up the reference case are obtained from the literature, and this creates uncertainty in the energy system (O'Ryan et al. 2020; Phimister and Roberts, 2017). And also, CGE models have a strong disadvantage of a high-level aggregation that makes them unsuitable to evaluate specific technology policy shifts (Bachner et al. 2019). However, a high-level aggregation in CGE modeling has the advantage of lesser usage of data as compared to

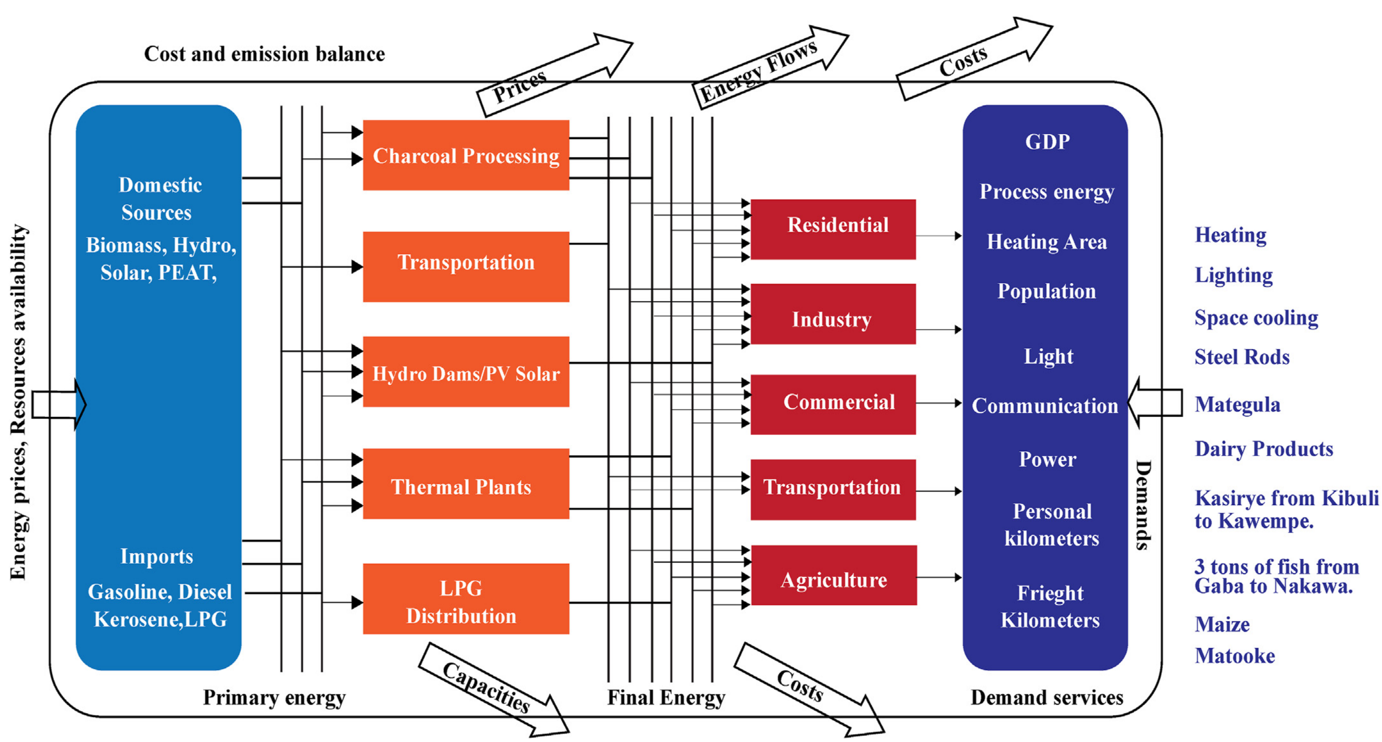

Figure 3. Reference energy system.

TIMES-VEDA modeling when establishing the baseline conditions. Because of the inherent limitations and strengths in both bottom-up and top-down modeling frameworks, the new standard is to merge them and generate a “hybrid” framework. In this way, an addition of specified technologies in a top-down model is realized, such as Sassi et al. (2010) or economy-wide effects are introduced in bottom-up frameworks, such as Lekavicius et al., 2019. The authors have planned a study to develop a GKMA-CGE model as a mitigation for the limitations of the GKMA-TIMES model to examine the economy-wide effects of its energy impacts for a robust energy policy design.

5. Results and findings

The GKMA-TIMES model results demonstrate policy options by considering the supply energy mix; electrical power production by fuel type; energy demand by sector & fuel type; carbon emissions by sector & fuel type; and the total system cost for the Sustainable Energy Portfolio of the GKMA over the planning horizon.

5.1. Primary supply options

The results show that over the planning horizon, the primary energy requirements will grow by 60.36% compared to the base year conditions (Table 2). The increased economic activities, population growth, improvement in the standard of living in GKMA, and increased displacements within the metropolitan are the major contributors to the increase in the primary supply mix as compared to the base year conditions. However, due to the low-carbon policies imposed on the model, the results indicate a significant decrease in the uptake of the primary mix and the stabilization of the consumption of fossil fuels over the planning period.

5.2. Electrical power production by fuel type

The results suggest that GKMA should increase electricity generation from 6.1 TWh to 322 TWh, mainly from hydro and PV-Solar technologies for sustainability (Figure 4). The results also indicate that there would be a decrease in uptake of Biofuels and Charcoal in electrical power production throughout the planning period as a policy intervention to mitigate CO_2 emissions. Most of the generated electricity is planned for the electrified Kampala metro resulting in less uptake of fossil fuels. This result indicates that low-carbon electrification would be essential for sustainability.

5.3. Energy demand by fuel type

The results show the share of electricity increasing by 53.68%, becoming the major contributor to fuel consumption for sustainability (Figure 5). The share of refined fossil fuels maintains a constant share to cater for the transportation demand, allowing the energy system to deploy more low-carbon electrical power and biofuels as a stratagem to abate CO_2 emissions. The electricity would be consumed more in the passenger railway category. This result suggests that management should set up an electrified railway system to switch travelers from the road transportation to the metro for sustainability. Despite the significance of charcoal fuel for heating, its share in the final energy remains low as more of the population gets access to low-carbon electricity.

5.4. Energy consumption by sector

The results indicate an increase in the final demand from 139.6PJ to 497.42PJ (Table 3). Transportation is the largest consumer of final energy (49.2%). The passenger land transportation, industrial, residential and commercial sectors show a huge potential for final energy demand. The energy-intensive technologies in the industrial sector, low efficient technologies for heating in the residential sector, and the proposed electrified Kampala metro account for the higher consumption of the final energy demand by sector.

5.5. Energy consumption by industrial sub-sector

The industrial sector comprises Food & Drink, Steel & Iron, Brick and Paper Industries, and Chemical & Plastic, Broadcasting & Telecasting, and telecommunication industries which are classed as other industries (UBOS, 2016). The results indicate that Food & Drink dominates energy demand (55%) as shown in Table 4. The larger energy intake in Food & Drink is attributed to the increasing demand for foods & beverages as the metropolitan’s population increases.

5.6. Energy consumption by the residential sector

The final energy demand for the residential sector is summarized and illustrated in Figure 6. The results indicate that the Heating (cooking, water heating, and space heating) subsector dominates energy consumption for the residential sector at 92%, over the planning period.

5.7. Energy consumption by the transportation sector

Energy demand in transportation increases significantly to cater for the proposed electrified Kampala metro and increased movements resulting from the increased population (Figure 7). The metropolitan depends on imported refined petroleum through Mombasa, Kenya. Petroleum demand reduces by 45.21% when 90% of road passengers switch to the passenger railway category. Therefore, the construction of an electrified Kampala metro becomes the central focus for policy changes over the planning period.

5.8. CO_2 emissions by sector

The analysis of the GKMA-TIMES model shows that the CO_2 emissions would increase in throughout the planning horizon due to an increase in economic activities (Table 5). The total CO_2 emissions increase from 4.6mtns to 6.99mnts in 2050. The biggest emitter is the industrial sector followed by transportation and then the residential sector.

Table 2. The Primary Supply mix (PJ).

Low-Carbon Scenario									
Energy type (PJ)	2015	2017	2020	2025	2030	2035	2040	2045	2050
Biofuels	76.14	72.50	81.17	98.84	102.34	114.62	120.11	142.61	154.22
Charcoal	18.6	15.93	13.80	10.61	11.53	14.33	21.68	32.31	35.2
Oils	37.728	37.95	37.64	37.92	38.74	39.31	41.04	44.22	47.30
Renewables	15.75	14.99	14.99	14.99	14.99	14.99	15.00	0.07	0.96
Total	**148.218**	**141.38**	**147.59**	**162.36**	**167.61**	**183.27**	**197.84**	**219.21**	**237.68**

Figure 4. Electrical Power Production by Fuel type.

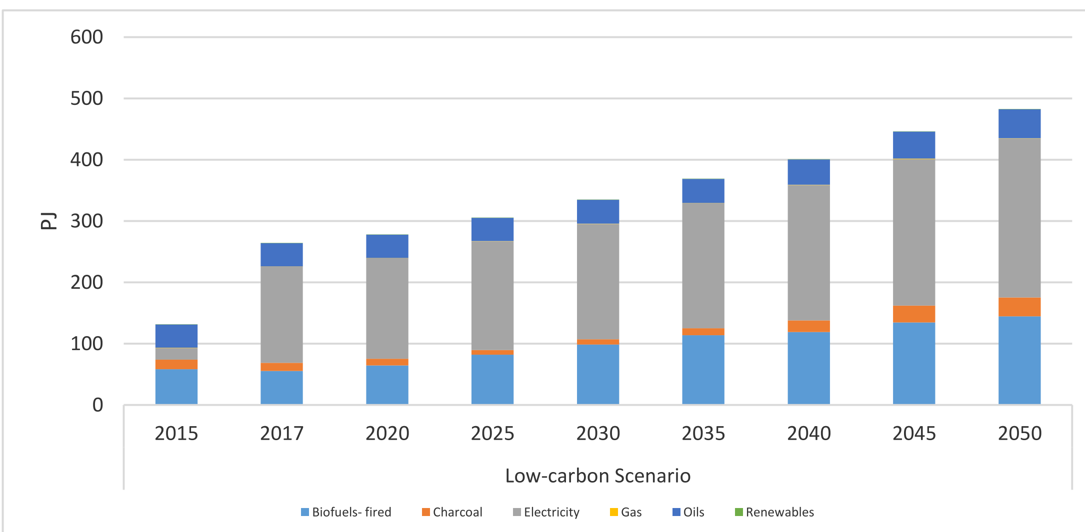

Figure 5. Energy Demand by Fuel type.

Table 3. Energy consumption by sector.

Low-Carbon Scenario									
Energy type (PJ)	2015	2017	2020	2025	2030	2035	2040	2045	2050
Agriculture	2.85	2.77	2.91	3.19	3.49	3.89	4.33	4.79	5.38
Commercial	9.19	9.03	8.98	8.81	9.3	10.0	10.77	11.8	13.05
Industrial	61.4	62.17	62.06	66.31	70.98	81.35	90.95	113.65	120.88
Residential	40.87	36.92	44.86	59.35	73.83	85.66	93.52	100.86	113.38
Transportation	28.82	160.78	166.70	176.26	186.38	198.50	212.41	228	244.74
Total	**139.6**	**271.67**	**285.51**	**313.93**	**343.97**	**379.4**	**411.98**	**459.09**	**497.42**

Table 4. Energy consumption by industrial sub-sector.

Low carbon Scenario									
Energy type (PJ)	2015	2017	2020	2025	2030	2035	2040	2045	2050
Food & Drink	24.03	24.45	25.26	27.08	29.22	36.76	43.31	62.81	66.48
Iron & Steel	14.94	17.23	15.66	16.59	17.5	18.62	19.82	21.05	22.46
Brick	12.24	9.5	9.8	10.52	11.28	12.1	12.97	13.9	14.9
Paper & Print	1.89	1.92	1.99	2.13	2.29	2.45	2.63	2.81	3.01
Other	8.3	9.06	9.33	9.98	10.68	11.43	12.23	13.08	14.01
Total	**61.43**	**62.17**	**62.07**	**66.31**	**70.98**	**81.35**	**90.95**	**113.65**	**120.88**

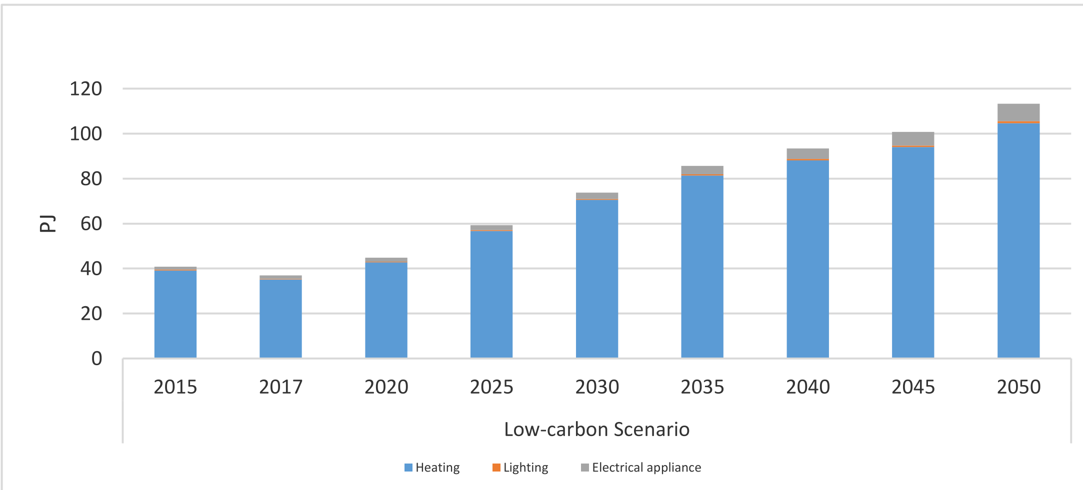

Figure 6. Consumption by the residential sector.

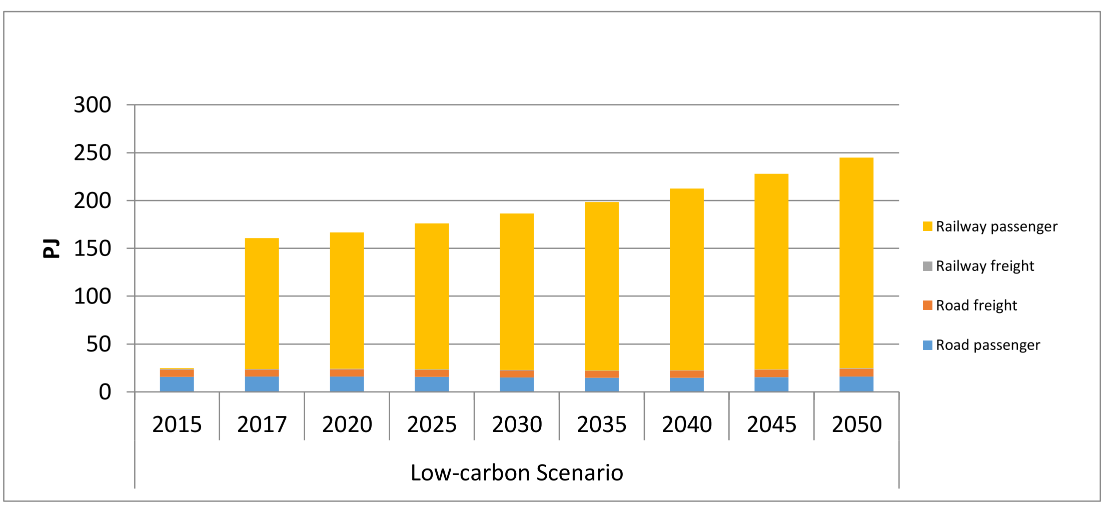

Figure 7. Energy consumption by the transport sector.

5.9. CO_2 emissions by fuel type

The analysis of the GKMA-TIMES model shows that the CO_2 emissions will increase in the energy management system throughout the planning horizon because of increasing fuel demand (Table 6). The total CO_2 emissions increase from 4.6mtns to 6.94mnts by 2050. The biggest emitter is Charcoal, followed by Diesel and Gasoline.

5.10. Annual expenditures

The analysis shows that total expenditures will increase from 2.053Bn$ to 5.94Bn$ (Table 7). Fuel expenditures contribute more to annual expenditures. The annualized investment cost in the demand sectors is the fastest growing expenditure.

Table 5. CO_2 Emissions by sector.

Low-Carbon Scenario

CO_2 emissions (ktn)	2015	2017	2020	2025	2030	2035	2040	2045	2050
CO_2Agriculture	122.61	113.37	118.46	130.53	141.82	158.30	176.23	193.34	216.261
CO_2Commercial	56.77	51.39	45.33	34.63	30.3	25.05	19.33	39.22	21.30
CO_2Industrial	1537	1477.61	1458.4	1579.72	1748.01	1883.42	2029.82	2188.46	2347.77
CO_2Power Generation	0	0	0	0	0	0	0	0	0
CO_2Residential	876.67	693.22	468.82	84.38	100.47	330.69	1017.98	187.1	2138.16
CO_2Transportation	1734.61	1738.16	1744.01	1708.68	1674.46	1627.75	1653.32	1725.92	1810.87
Total	**4622.55**	**4353.9**	**4115.17**	**3818.09**	**3975.2**	**4305.37**	**5176.63**	**6473.72**	**6990.04**

Table 6. CO_2 Emissions by fuel.

Low-Carbon Scenario

CO_2 fuel emission (ktn)	2015	2017	2020	2025	2030	2035	2040	2045	2050
Charcoal	1867.8	1599.18	1383.36	1060.74	1156.63	1436.26	2178.64	3247.7	3539
Diesel fuel	1464.96	1495.19	1470.72	1513.84	1563.08	1617.77	1699.6	1801.86	1911.87
Fuel Oils	116.1	114.164	111.79	109.27	113.66	118.27	122.88	128.36	133.93
Gasoline	1039.5	1043.9	1041.53	1013.39	981.70	940.98	949.5	986.53	1037.02
Kerosene	92.61	58.64	59.73	63.16	93.33	107.81	123.92	141.85	161.76
LPG	10.73	26.26	29.9	36.54	45.16	55.58	68.69	128.56	161.28
Total	**4591.69**	**4337.35**	**4097.03**	**3796.93**	**3950.55**	**4276.67**	**5143.23**	**6434.86**	**6944.85**

Table 7. Annual expenditures.

Low-Carbon Scenario

System Expenditure (mn$)	2015	2017	2020	2025	2030	2035	2040	2045	2050
Annual activity cost	94.45	89.93	89.96	90.02	68.88	68.83	68.88	0.94	2.12
Annual fixed operating and maintenance costs	367.42	379.47	434.51	541.12	632.16	736.64	822.89	929.80	1029.48
Fuel Expenditures	1591	1448	1448	1570	1665	1813	2031	2362	2639
Annualized Investment (Demand)	0	130	345	715	1086	1431	1612	1798	2004
Annualized Investment (Conversion)	0	0	0	0	0	0	0	177	262
Total	**2053**	**2047**	**2317**	**2916**	**3448**	**4049**	**4535**	**5268**	**5936**

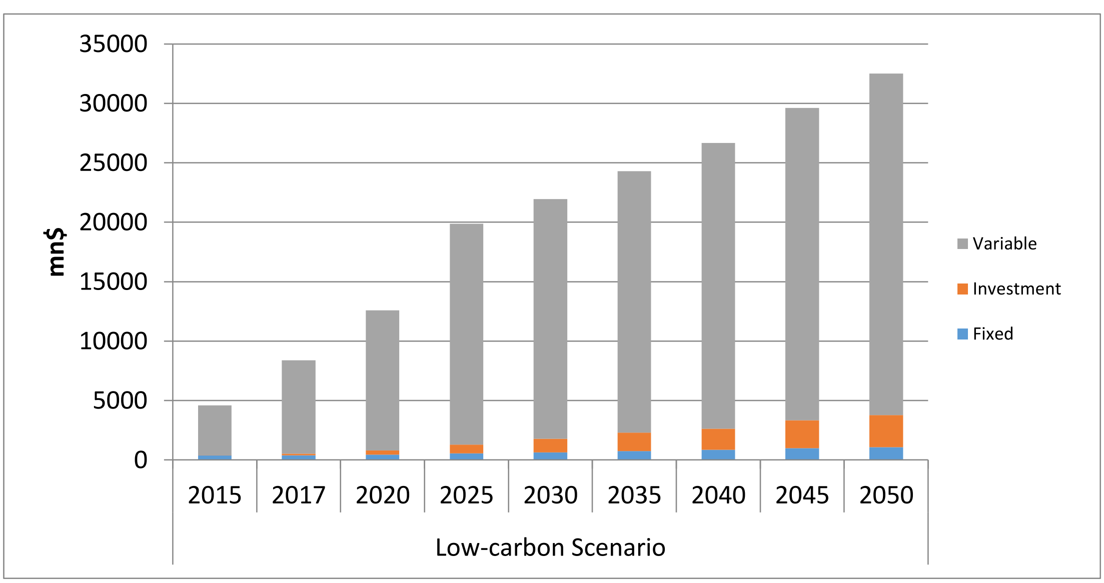

Figure 8. Total annual system cost.

5.11. Annual system cost

The annual system cost increases from 4.58Bn$ to 32.5Bn$ as shown in Figure 8. The annualized system cost suggests that management should invest in the sustainable energy portfolio over the planning period. The overall results of the study indicate a mandated optimization of the primary mix, low-carbon electrical power production from hydropower and solar energy technologies, and the setting up of an electrified Kampala metro for sustainability.

TIMES-VEDA model generator maintains a strategic significance in the development and analysis of sustainable energy portfolios. The results obtained in this study show consistency of its endogenous parameters in developing low-carbon societies for economies worldwide. Compared to other studies that employed the same methodology such as Chiodi et al., 2013, the analysis of the GKMA-TIMES model shows dependability of this bottom-up framework in determining an optimized primary supply energy, energy consumption, and specific carbon abatement strategies in electricity generation, residential, commercial, agricultural, industrial & transportation demand sectors.

6. Discussion of GKMA-TIMES results from a policy perspective

I The electrical power production sector should significantly transform during the planning horizon. A need to inject a significant amount of low-carbon electricity and raise its share in the energy balance from the current 1.4%–53.68% for sustainability is dominant. The GKMA-TIMES model analysis suggests that low-carbon electrical power production from hydropower and PV-Solar technologies is achievable because the metropolitan is endowed with an abundant hydropower potential of 2000MW and it is located astride the equator, with 5.1 kWh/m^2 of solar energy available daily.

Historically, hydropower plants have dominated the electrical power production fuel mix (95%) in the metropolitan. The analysis of the GKMA-TIMES model shows that over the planning period, the electrical power production sector needs a significant transformation. The necessity to enhance the electrical power security and the abatement of CO_2 emissions are the major reasons for this change. Because hydropower is a low-carbon fuel, its use for electrical power production should be optimized with a supplement of PV-Solar technologies. On the demand side, the passenger land transportation, industrial, residential, and commercial sectors offer large potential for electrical power demand as the metropolitan urbanizes. The GKMA-TIMES model analysis further shows that changing the sectoral economic structure, use of hybrid vehicles and the establishment of an electrified Kampala metro can soothe the electrical power demand throughout the planning period.

II. The demand for fossil oils would continue to rise during the planning period. To control its consumption, the establishment of an electrified Kampala metro becomes the central focus for policy changes if the metropolitan is to achieve sustainability.

The demand for fossil fuels is expected to rise by 25.36% over the planning horizon. At present, GKMA is still 100% dependent on imported refined fossil oils mostly via Kenya from the middle east. The construction of the first refinery in Uganda is yet to be realized. The refinery could meet 100% of GKMA's demand for petroleum products and thus reduce substantially the dependence on imported refined fossil oils that exposes the metropolitan to the traditionally unstable world oil market. The GKMA-TIMES model analysis shows that the consumption of fossil fuels in the transportation sector would reduce if management sets up an electrified Kampala metro and switches 90% of the passengers to the railway category. Management should invest heavily in a Kampala metro system with suggested exchanges at the current Clock tower junction, Wandegeya Junction, The Yard junction, and the central exchange constructed underneath present Amber House on Kampala Road with more substations accessible across the metropolitan. This study proposes the inter-exchange at Gare du Nord in downtown Paris to provide answers to core design questions and/or implement something similar to the current Dubai metro in UAE.

III. The analysis shows a gradual decline in the use of biomass in the supply energy. The future of biomass in GKMA's energy management system would depend on the afforestation rate, absorption rate of low-carbon electricity, LPG, and advanced technologies (such as the clay stove & briquettes) for heating in commercial, residential, and industrial sectors.

The GKMA-TIMES model shows that the hefty presence of woody biomass in the primary supply energy will continue to rise unless the metropolitan switches to the sustainable energy portfolio. For instance, its analysis shows that over the planning period, charcoal availability in the primary supply energy will decline to 14.81% in the sustainable energy portfolio. The decline in charcoal demand is premised on the fact that the electrical power and LPG will be absorbed gradually in the energy management system.

IV. CO_2 emissions increase from 4.6 mts to 7 mts by fuel type. CO_2 emissions reduction strategies should target low-carbon electrical power production, establishment of the Kampala metro, and deployment of advanced technologies in heating sectors.

The restructuring of the electrical power production sector shows the highest potential for the establishment of a sustainable energy portfolio for GKMA towards 2050. This is because GKMA has a larger room for fuel switching for low-carbon electrical power production to reduce CO_2 emissions. The GKMA-TIMES analysis suggests that low-carbon electrical power production from hydropower and PV-solar is achievable. Therefore, management should invest in the hydropower and PV-solar technologies for sustainability. For feasible CO_2 emissions abatement in the transportation sector, management should set up the electrified Kampala metro for sustainability. In the residential heating sub-sector, carbon abatement is by gradual fuel switching from charcoal to low-carbon electricity and LPG in suburban areas over the planning period. Also, the metallic stoves (SIGIRI) should be replaced with clay stoves to enhance efficiency. The use of a 3-stone stove (Ekyo'to) in the rural GKMA should be abolished to mitigate the CO_2 emissions. The GKMA-TIMES model analysis shows that residential heating in the rural areas contributes more to the CO_2 emissions that cumulatively cause global warming.

7. Conclusion and policy implications

The results from the GKMA-TIMES model demonstrate how energy supply resources and associated technologies can be optimized to meet projected demand in commercial, residential, industrial, transportation, agricultural, and electricity generation activities. A sustainable energy portfolio for Greater Kampala Metropolitan Area is a low-carbon scenario endowed with CO_2 abatement strategies that guarantee a carbon footprint for the metropolitan towards 2050. The study demonstrates the efficacy of the TIMES-VEDA modeling framework in answering the key research questions leading to a sustainable energy portfolio for GKMA towards the mid-century. The analysis suggests that the primary supply energy should be optimized and comprises biofuels (64.9%), charcoal (14.8%), fossil fuels (19.9%), and renewables (0.4%) for sustainability. Hydropower and PV-Solar-based technologies are the ultimate choices for sustainable low-carbon electrical power production. The share of electricity should be increased by 53.68% in the final demand by fuel type, to become the major contributor to fuel consumption for sustainability. The analysis also suggests that energy demand by sector would increase from 139.6 PJ to 497.42 PJ and CO_2 emissions would increase from 4.6 mtons to 7 mtons. The cost of implementing the sustainable energy portfolio appears to be reasonable. However, for GKMA to attain sustainability, the establishment of an electrified Kampala metro and switching 90% of land passengers to the railway category becomes the central focus of any policy changes. Management should invest optimally in low-carbon electrical power production, transportation, industrial and residential sectors if sustainability is to be achieved by 2050. The energy impacts quantified in this study provide valuable insights for upholding the SDG-7 & SDG-11, and the Paris Low-carbon Roadmap. The experience gained in this study could benchmark energy policy design for other developing economies along the equator having access to plentiful renewable supply energy.

It is also necessary to assess the economy-wide impacts of the sustainable energy portfolio for the Greater Kampala Metropolitan Area on its economy using the Computable General Equilibrium (CGE) model and such a study has been planned.

Declarations

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

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Data included in article/supp. material/referenced in article.

Declaration of interest's statement

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Additional information

No additional information is available for this paper.

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Kimuli Ismail is a Ph.D. student in the department of Mechanical Engineering, and the research title for his Ph.D. thesis is 'Development of a Sustainable Low-carbon Footprint for the Greater Kampala Metropolitan Area: The Efficacy of a TIMES/CGE hybrid analysis.' Email: 73kimuli.ug@gmail.com;

Eng. Dr. Michael Lubwama is a senior lecturer in the Department of Mechanical Engineering at Makerere University Kampala, Uganda. His research interests revolve around the sustainability of energy and material systems. Email: michael.lubwama@mak.ac.ug;

Eng. Dr. John Baptist Kirabira is a professor and current chair in the Department of Mechanical Engineering at Makerere University Kampala, Uganda. His research interests include materials science and energy systems. Email: jbkirabira@cedat.mak.ac.ug

Eng. Dr. Adam Sebbit is a senior lecturer in the department of Mechanical Engineering at Makerere University Kampala, Uganda. He is an expert in modeling energy systems. Email: amsebbit@cedat.mak.ac.ug.