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Sustainable urban transportation planning: Integrating an electrified metro system into Kampala metropolis

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ABSTRACT

With the United Nations (UN) predicting that 60% of the global population will reside in cities by 2050, sustainable transportation planning is a prominent global trend. This study examines Kampala's transportation sustainability and addresses existing knowledge gaps. It leverages the TIMES-VEDA model, an acronym for "The Integrated MARKAL-EFOM System - Versatile Data Analyst." TIMES-VEDA is an engineering optimizer used to explore four scenarios: Business-as-Usual (BAU), Reduction in Electricity Consumption (REC), Renewable Electricity Portfolio (REP), and Carbon Reduction Target (CRT). These scenarios analyze the inherent aspects of the Kampala metropolis energy system, providing a foundation for evidence-based decision-making. The approach aligns with the United Nations' Sustainable Development Goals (UN's SDGs 7, 11, & 13), Uganda's Vision 2040, and the third National Development Plan (NDPIII). The analysis demonstrates that sustainability is within range and highlights the imperative of a holistic approach, the potential of mass rapid transit, anchored by an electrified metro system, to advance green mobility. It sheds light on sustainable practices and trade-offs among distinctive pathways, suggesting a mix of policy measures to combat climate change. The KAMPALA-TIMES model, a bottom-up framework, reveals that a region-specific policy package, particularly the CRT scenario, achieves significant decarbonization, promoting eco-friendly multimodal transportation and paving the way for a more sustainable future for Kampala until 2060. The findings inform policy on urban planning and sustainable transportation that is adaptable elsewhere, ensuring long-term environmental and economic resilience.

1. Background

Transportation has been recognized as a vital link impacting various aspects of global life for an extended period (Zhang et al., 2021; Sharifi et al., 2020). In this context, the world's natural environment, social well-being, and economic progress depend fundamentally on mobility (Cohen et al., 2020; De Neve & Sachs, 2020). The urban transportation system has faced challenges, contributing

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to environmental degradation due to heightened residential density, escalating travel demand, increased automobile ownership, and deteriorating traffic conditions (Shahzad & Cheema, 2024; Kwon et al., 2023). Metropolitan areas grapple with diverse traffic modes, encompassing passenger vehicles, commuter buses, trucks, and rail transit (Ulpiani et al., 2023). To effectively curtail city-wide energy consumption and greenhouse gas emissions (GHG), it is imperative to implement effective plans that integrate the interplay between differing trip modes (Xu et al., 2023; Hoang & Nguyen, 2021; Hunter et al., 2019). The motivation for this study stems from Kampala's pressing transportation and environmental challenges, hindering sustainable urban growth and quality of life. As Uganda's capital and economic hub, Kampala experiences rapid urbanization and increasing transportation demand, leading to traffic congestion, air pollution, and inefficient transit options. Despite the urgency, region-specific sustainable transportation studies addressing Kampala's unique conditions are scarce. This research aims to bridge this gap by proposing a data-driven approach to sustainable transportation planning aligned with global and national sustainability goals. It will provide actionable insights for policymakers and urban planners to improve Kampala's mobility and environmental performance. An optimized multi-modal mobility system, a simulated testbed extensively applicable to various traffic modes with a mass rapid transit (MRT) system having an electrified metro at its core, is proposed to enhance sustainability for the Kampala metropolis transportation sector (Kimuli et al., 2024). Furthermore, all proposed transportation solutions are designed to emphasize energy conservation, ensuring that each approach contributes to a sustainable and environmentally friendly urban transportation system (Lv, Z. & Shang, 2023; Bibri & Krogstie, 2020). This focus on energy-saving measures aligns with reducing the city's carbon footprint and promoting a resilient, resource-efficient infrastructure for Kampala's future mobility needs (Hassan S et al., 2024; Ramli et al., 2024).

As cities grow, sustainable urban mobility becomes increasingly crucial. Transportation engineering is pivotal in supporting energy-saving initiatives within smart cities, necessitating a multidisciplinary approach (Macioszek et al., 2022). Focusing on Kampala, this study builds on this foundation by employing a bottom-up engineering modeling approach to assess energy-saving potentials and develop sustainable transportation pathways tailored to the city's unique context. This approach addresses Kampala's growing congestion, emissions, and energy efficiency demands, aligning with global efforts for sustainable urban development.

Therefore, it is evident that while significant strides have been made globally in sustainable transportation planning, Kampala's unique challenges, such as rapid urbanization and inadequate public transportation infrastructure, necessitate a tailored approach. This study aims to fill the research gap using a bottom-up modeling approach with the TIMES-VEDA model and Schwartz scenario planning. By analyzing current transportation patterns and developing forward-looking scenarios, this study offers innovative solutions to improve urban mobility in Kampala while reducing environmental impact and supporting economic growth. The objectives are to provide a detailed energy consumption and emissions analysis, propose a viable multimodal transportation alternative, and deliver actionable policy recommendations that align with local needs and global sustainability targets.

Kampala, Uganda's capital, faces significant transportation challenges due to rapid urbanization and increasing demand (Kimuli et al., 2022; Pozhidaev, 2020). This study proposes a multi-pronged strategy to achieve sustainable urban mobility. Specifically, the study analyzes current travel patterns, develops future scenarios, evaluates their impacts using a bottom-up engineering model, and assesses the policy implications of a multimodal transportation plan centered around an electrified metro system. This approach addresses congestion, air pollution, and inefficient travel times, fostering a more sustainable and efficient transportation system for Kampala (Kimuli et al., 2023).

Sustainability, a multifaceted concept (Pascual et al., 2023; Ruggerio, 2021; Mensah, 2019), involves preserving Earth's natural systems and ensuring human well-being (Virtanen et al., 2020). In urban transportation, sustainability entails meeting present needs without compromising future generations (Joseph, 2021; Sekasi & Martens, 2021). This study adopts a bottom-up modeling approach to guide Kampala toward a sustainable urban mobility future. The emphasis is placed on attaining a harmonious fusion of energy, economic, and environmental factors during transportation modeling, with green mobility as a fundamental cornerstone of this initiative. (Hernández et al., 2023; Kuru & Ansell, 2020). By aligning with global and national sustainability goals, such as the UN SDGs and Uganda's Vision 2040, this research aims to contribute to a more sustainable and resilient Kampala (Mutambisi & Chirisa, 2023; Galuszka et al., 2021).

This study emphasizes the importance of green mobility in sustainable urban transportation planning, aiming to mitigate carbon emissions and improve air quality, public health, and climate change resilience (Din et al., 2023; Lee et al., 2022). The KAMPALA-TIMES model, a localized TIMES-VEDA framework, proposes decarbonization initiatives aligning with global research on sustainable transportation solutions (Ismail et al., 2023; Smeds & Cavoli, 2021; Moradi & Vagnoni, 2018).

This study aims to promote sustainable transportation in Kampala by proposing a diversified energy supply, reducing carbon emissions, optimizing trip modes, decreasing fossil fuel reliance, and establishing an electrified metro system as the backbone of the transportation network.

This study aims to answer the following questions: What is the current state of urban transportation in Kampala, including energy consumption patterns, modal shares, and emissions profiles? Considering energy demand, emissions reductions, and modal shifts, how will various decarbonization strategies affect Kampala's mobility landscape? How can the energy supply be optimized to enhance green mobility in Kampala, considering the potential of renewable energy sources and energy efficiency measures? Finally, how can the scenario outcomes inform sustainable urban transportation development policy that aligns with Kampala's strategic environmental and economic goals?

This study aims to provide a comprehensive framework for promoting green mobility in Kampala, contributing to a more sustainable and resilient urban transportation system.

1.1. Limitations and assumptions

While this study offers valuable insights for sustainable transportation planning in Kampala, several limitations merit consideration. The model's robustness is inherently tied to the accuracy and comprehensiveness of available data. Any limitations or inaccuracies within these datasets could influence the precision of the findings. Additionally, while a powerful tool, the TIMES-VEDA framework employs inherent assumptions and simplifications that may not fully capture the complexities of Kampala's transportation system. The study's focus on optimizing energy supply, trip modes, GHG emissions reduction, and transportation efficiency provides a strong foundation for green mobility. However, emerging trends or unforeseen developments within the dynamic transportation landscape may only partially reflect the scenarios explored.

While the study offers a strong foundation for green mobility, successful implementation will depend on effective policy implementation, public acceptance, and stakeholder collaboration. To address the dynamic nature of transportation systems, ongoing refinement and adaptation are necessary. Nonetheless, these limitations do not undermine the overall value of the study; instead, they highlight the dynamic nature of transportation planning and the ongoing necessity for methodological improvement and adaptation.

1.2. Novelty

This study is a pioneering contribution to transportation policy development in Kampala. It integrates the TIMES-VEDA modeling framework with Schwartz scenario planning. It offers novel insights into urban mobility challenges and proposes a transformative approach with an electrified metro system as the backbone. This study aligns with global and local sustainability agendas, providing a valuable model for other cities seeking sustainable and equitable transportation systems.

Furthermore, the study's proposal to introduce a Mass Rapid Transit (MRT) system anchored by an electrified metro is innovative in Kampala's transportation landscape. Incorporating advanced technologies for system monitoring, fare collection, and passenger information systems demonstrates a forward-thinking approach to urban mobility planning.

Therefore, this study's unique methodological approach, focus on green mobility, and innovative transportation solutions collectively represent a significant advancement in sustainable urban transportation planning. The findings address Kampala's pressing mobility challenges and offer a scalable model for other cities striving to achieve sustainable and equitable transportation systems.

The rest of the paper is organized systematically to facilitate comprehensive analysis and understanding. It begins with a literature review that contextualizes the study within existing research. It explores the global and regional challenges in sustainable urban transportation and the theoretical frameworks underpinning low-carbon mobility solutions. This is followed by the methodology section, which details the mixed-methods approach used to gather primary and secondary data, a Schwartz scenario planning methodology, and the TIMES-VEDA optimization model to analyze proposed transportation interventions' energy and emissions implications. The analysis and discussion section presents the scenario development findings, examining each scenario's impacts on energy demand, emissions, and sustainable transportation outcomes in Kampala. The conclusion synthesizes the research insights, underscoring the potential for transformative urban mobility through electrification and multi-modal integration. Finally, the policy implications section offers actionable recommendations for policymakers, emphasizing adopting green mobility practices, investment in electrified transit infrastructure, and strategic urban planning to foster Kampala's sustainable and resilient transportation future.

2. Literature review

This study reviews existing literature to identify knowledge gaps and challenges in Kampala's sustainable transportation planning. This review provides a rationale for selecting the most appropriate methodology to address these gaps and develop effective urban mobility solutions.

2.1. State of Kampala transportation

Kampala faces significant transportation challenges, including congestion, inadequate infrastructure, and reliance on fossil-fuel vehicles. Rapid urbanization and population growth have exacerbated these issues, leading to air pollution and environmental degradation (Kimuli et al., 2024). The lack of a robust public transit system and insufficient pedestrian infrastructure exacerbate Kampala's transportation challenges. These lead to inequitable access, safety concerns, increased congestion, air pollution, and infrastructure strain.

Existing literature highlights the need for strategic urban transport planning in African cities (Kamana et al., 2023; Durant et al., 2023). However, there is a gap in research specific to Kampala. This study addresses this gap by leveraging a bottom-up approach and Schwartz scenario planning. It considers three more alternate scenarios to explore sustainable transportation futures. The goal is to develop targeted, evidence-based interventions to enhance urban mobility, mitigate environmental impacts, and bolster Kampala's resilience.

2.2. The ministry of works, housing and transport

The Ministry of Works, Housing, and Transport (MoWHT) is integral to guiding policy and providing strategic oversight for Uganda's transportation sector. Within the Ministry, the Department of Transport Planning, led by the Commissioner of Policy and

Planning, is tasked with initiating, formulating, and coordinating transportation policies. It undertakes comprehensive planning, monitoring, and coordination efforts to implement sector development plans, such as the National Transport Master Plan, while maintaining a robust infrastructure and performance database to support evidence-based decision-making (Stewart, 2024). Additionally, the department is pivotal in budgetary processes, collaborating with the Ministry of Finance, Planning, and Economic Development to prepare budget framework papers, policy statements, and detailed budget estimates. These initiatives ensure effective planning, management, and development of Uganda's transportation sector.

Despite the MoWHT's overarching role in national policy oversight, a critical research gap exists in the absence of targeted policies specifically addressing Kampala's unique transportation challenges. Recent literature, exemplified by McAslan et al. (2024) and Sasidharan (2023), underscores the importance of region-specific transportation planning to effectively address urban areas' diverse and complex mobility needs. However, empirical studies focusing on tailored strategies for Kampala's urban context remain limited.

This study aims to bridge this gap by proposing region-specific strategies for sustainable urban mobility in Kampala. Leveraging the KAMPALA-TIMES model, a bottom-up research framework, the study provides granular insights into the city's transportation dynamics and explores the potential impacts of various policy interventions. This approach aligns with the growing recognition of the need for localized, evidence-based policies that can effectively enhance urban mobility and sustainability in Kampala.

2.3. Uganda vision 2040

Uganda Vision 2040 establishes an ambitious roadmap for the country's transformation into a competitive upper-middle-income nation by 2040. It underlines the critical role of advanced transportation infrastructure in driving socio-economic development (Olwor, 2023). Drawing inspiration from the successful utilization of expansive railway networks in countries like China and India, the Vision calls for the rapid development of a comprehensive transportation network, particularly within Uganda's burgeoning urban centers.

Key priorities include constructing a standard-gauge railway (SGR) system connecting major border points and ports and substantially improving road infrastructure, including multi-lane expressways linking key cities and economic hubs. The Vision recognizes the challenges of urban congestion and pollution and advocates for developing mass rapid transit systems, such as light rail, bus rapid transit (BRT), and trams, extending into urban centers and emerging regional cities (Muwanguzi et al., 2018).

While Uganda Vision 2040 provides a broad national framework for infrastructure development, a notable research gap persists in formulating specific policies and strategies tailored to Kampala's unique transportation dynamics. Existing literature underscores the importance of region-specific transportation planning in addressing rapidly growing African cities' diverse and complex mobility needs (Chirisa et al., 2023; Virág et al., 2022). However, Kampala's specific context remains under-explored in scholarly and policy discourse.

This study addresses these gaps by employing a Schwartz scenario planning approach, leveraging the KAMPALA-TIMES model, a bottom-up engineering framework, to explore sustainable transportation futures and identify tailored policy options for the metropolis. This approach facilitates a detailed, context-specific analysis of potential pathways for the city's transportation system, ensuring alignment with both national aspirations articulated in Uganda Vision 2040 and the specific realities and challenges of the Kampala Metropolis.

2.4. National development plan III (NDPIII)

Uganda's National Development Plan III (NDP III) aims to achieve upper-middle-income status by 2040 through sustainable industrialization and inclusive economic growth (Guloba et al., 2019). The plan prioritizes infrastructure development, including transportation, as a critical driver of economic growth. However, Uganda's current transportation infrastructure faces challenges, including a heavy reliance on road transport, high operational costs, and weak institutional frameworks (Mwangu, 2023). These issues hinder the country's competitiveness and limit its ability to capitalize on regional and global trade opportunities.

NDP III aims to develop a seamless, safe, inclusive, and sustainable multimodal transportation system (Guloba et al., 2019). While NDP III provides a comprehensive national framework, specific policies tailored to Kampala's unique challenges are needed (Kimuli et al., 2024).

Urban transportation planning requires tailored, city-specific strategies (Reinwald et al., 2024; Even–Levi & Kissinger, 2023). With its rapid urbanization and unique challenges, Kampala needs a focused approach beyond the national framework of NDP III (Kimuli et al., 2024).

This study aims to bridge this gap by employing the KAMPALA-TIMES model, a bottom-up, engineering-focused approach, to assess region-specific energy impacts and inform sustainable urban transportation planning in Kampala. By providing granular insights and evidence-based recommendations, this research directly contributes to realizing NDP III's objectives of fostering a more sustainable, efficient, and inclusive transportation infrastructure in Uganda's capital city, enhancing the plan's relevance and applicability at the city level.

2.5. Kampala physical development plan (KPDP)

The Kampala Physical Development Plan (KPDP) recognizes the city's environmental challenges. To support urban expansion and economic growth, it aims to improve efficiency and connectivity through infrastructure development, including radial highways and concentric ring roads (Wabineno-Oryema, 2018).

The KPDP focuses on road-based solutions, overlooking the potential benefits of an electrified metro system (Lin et al., 2024; Chiquetto et al., 2024; Lin et al., 2022). Given Kampala's rapid population growth and increasing mobility needs, this omission represents a significant gap in the city's sustainable urban transportation planning landscape.

Recent literature emphasizes the need for a diversified approach to transportation infrastructure in cities like Kampala (Kimuli et al., 2024). Integrating a metro system can offer a sustainable, efficient, and high-capacity alternative, reducing dependency on fossil fuels and lowering operational costs (Corazza, 2024; Morte et al., 2023; Olabi et al., 2023). This aligns with global efforts towards sustainable development.

This study addresses the gap in the KPDP by using the KAMPALA-TIMES model to evaluate the energy implications of an electrified metro system. It provides actionable insights for urban planners and policymakers to develop strategies for a more sustainable, efficient, and resilient transportation system in Kampala.

2.6. Study alignment with the SDGs & the Paris accord

The study employs the KAMPALA-TIMES model to address crucial elements of the Sustainable Development Goals (SDGs) 7, 11, and 13 and the Paris Agreement's climate action commitments. The study emphasizes optimizing the energy supply within Kampala's transportation sector through a comprehensive modeling approach to advance affordable and clean energy (SDG 7). By focusing on energy efficiency and renewable energy integration, the study underscores the role of an electrified metro system as a pivotal component in establishing a sustainable mass rapid transit system. This aligns with global best practices advocating electrified public transport as a critical strategy for achieving low-carbon urban mobility (Hou et al., 2023).

Furthermore, the KAMPALA-TIMES model's capacity to evaluate and implement greenhouse gas (GHG) abatement strategies aligns with the objectives of SDG 13 (climate action) and the Paris Agreement's goal of limiting global temperature rise to well below 2°C. The model's optimization of various transportation scenarios provides an evidence-based framework to assess the potential for reducing GHG emissions by adopting electrified transport infrastructure. This is particularly relevant in Kampala, where rapid urbanization and increasing transportation demands necessitate urgent climate action measures (Kimuli et al., 2024).

By optimizing transportation efficiency, the study contributes significantly to creating sustainable cities and communities (SDG 11) by proposing interventions that reduce traffic congestion, lower air pollution levels, and improve public health outcomes. Integrating an electrified metro system is highlighted as a transformative intervention, offering substantial co-benefits, including reduced fossil fuel dependency, enhanced urban air quality, and increased accessibility to public transportation networks (Winkler et al., 2023).

However, a gap exists in the current body of research concerning the detailed energy implications and policy frameworks required for the electrification of metropolitan transport systems in developing cities like Kampala. This study aims to bridge this gap by providing a region-specific analysis of energy supply and consumption, sector and fuel type emissions, and cost factors associated with integrating an electrified metro system into Kampala's transport infrastructure. Through its findings, the study offers critical insights for policymakers and urban planners to develop integrated and sustainable urban transportation strategies that align with both the SDGs and the Paris Agreement, ensuring a more sustainable and resilient urban future for Kampala.

2.7. A need for an engineering bottom-up approach in Kampala transportation planning

Sustainable transportation planning fundamentally evaluates operational and managerial dimensions across various modes to ensure safe, efficient, and environmentally friendly mobility (Jeon et al., 2013). Traditional top-down planning methods often fail to capture in-depth urban environments' unique characteristics and specific needs, particularly in rapidly urbanizing cities like Kampala. In contrast, a bottom-up modeling framework provides a more granular and flexible approach, enabling a comprehensive integration of diverse transportation modes and promoting eco-friendly alternatives within sustainable urban transportation systems (Anthony Jnr, 2023; Chang et al., 2019).

This study's adoption of a bottom-up approach is crucial for understanding the complex dynamics of Kampala's transportation landscape. Unlike top-down approaches that rely on aggregate data and assumptions, bottom-up models such as TIMES-VEDA focus on individual trip modes—including buses, sedans, trucks, motorbikes, and trains—and their interactions with economic activities and environmental impacts. This detailed perspective allows for a nuanced analysis of the potential effects of various interventions and scenarios. Previous studies, including Pina & Tchepel (2023), Besagni & Borgarello (2020), Hache et al. (2019), du Can et al. (2019), Park et al. (2018), Alam et al. (2017), Goulias & Konduri (2014), and Yeh et al. (2008), have demonstrated the efficacy of bottom-up frameworks in capturing the complex interplay between infrastructure, ridership, emissions, and policy measures.

By employing an engineering bottom-up methodology, this study seeks to provide a granular analysis of Kampala's transportation infrastructure, ensuring that the city's unique requirements and socio-economic dynamics are fully addressed. This approach facilitates a detailed examination of each mode's energy supply and consumption, greenhouse gas (GHG) emissions, and potential for sustainability improvements. Also, it allows for developing targeted solutions that reflect Kampala's specific context and priorities. The KAMPALA-TIMES model, a bottom-up engineering framework, is well-suited for exploring the city's energy-economic-environment (E3) nexus, providing valuable insights into the interdependencies between urban mobility, energy use, and environmental sustainability.

Moreover, the bottom-up framework fills critical knowledge gaps by incorporating region-specific energy impacts and diverse green mobility perspectives, offering a more robust foundation for policy formulation and urban planning. By enabling a detailed exploration of how different transportation interventions affect energy consumption, economic growth, and environmental quality, this approach promises significant advancements in sustainable urban transportation planning, particularly for cities in the Global

South facing rapid urbanization and growing sustainability challenges. Thus, adopting an engineering bottom-up framework in this study is not just a methodological choice but an essential strategy for advancing sustainable multimodal transportation planning in Kampala, ensuring alignment with local needs and global sustainability goals.

2.7.1. Research gap identified

The literature review identified a critical gap in sustainable transportation solutions explicitly tailored for Kampala. While numerous studies emphasize the importance of adopting low-carbon transportation strategies, existing research primarily focuses on cities in developed regions, where the infrastructural and socio-economic conditions differ significantly from those in African metropolises (Sovacool et al., 2022; Beitelmal et al., 2024). Such studies underscore the necessity of innovation to tackle urban mobility and emissions challenges in growing cities like Kampala, which faces unique obstacles such as limited public transport options, high reliance on informal modes of transport, and rapidly increasing vehicular emissions (Ho & Tirachini, 2024). This gap reveals a lack of region-specific modeling approaches that consider African cities' socio-economic and infrastructural dynamics. This study aims to adapt and implement transformative measures within Kampala's transportation sector by examining successful sustainable urban transportation strategies implemented in other urban contexts. This approach bridges the knowledge gap and paves the way for a more sustainable and economically viable future for Kampala's urban mobility landscape.

Furthermore, the TIMES-VEDA modeling framework has been identified as a robust tool for assessing various policy and technology scenarios' energy, environmental, and economic implications. Previous studies, such as those by Pina & Tchepel (2023) and du Can et al. (2019), have demonstrated the utility of a bottom-up approach in optimizing complex, multi-sectoral urban systems and evaluating the long-term impacts of transportation policies on emissions and energy consumption. However, TIMES-VEDA application to African cities, particularly Kampala, remains limited. We adopt a bottom-up, data-driven approach to scenario analysis by leveraging the TIMES-VEDA model in this study. This allows for an in-depth exploration of potential pathways to achieve green mobility within the Kampala metropolis. This framework supports evidence-based decision-making by providing insights into the trade-offs and outcomes of different policy interventions under diverse scenarios, thereby addressing the critical gaps in the existing literature on sustainable urban transportation planning in African contexts. This study aims to contribute to the body of knowledge by demonstrating the applicability of TIMES-VEDA in a developing city setting and offering a model for future research on sustainable urban transportation across similar urban environments.

3. Methodology

This study adopts a mixed-methods approach to examine the sustainability of Kampala's urban transportation system, combining qualitative and quantitative data to analyze the city's unique transportation challenges comprehensively. The rationale for employing a mixed-methods approach lies in its ability to leverage the strengths of both qualitative and quantitative methodologies, yielding a more holistic understanding of complex transportation dynamics. According to Saheb, T. & Saheb, T. (2024), mixed-methods research is particularly suited to studies that address multifaceted issues involving human behavior, policy implications, and technological applications, as it allows for an in-depth examination of social and environmental contexts alongside empirical data analysis. In transportation studies, integrating qualitative and quantitative data has enhanced the robustness of findings and provided actionable insights for decision-makers (Nickdoost et al., 2024).

Primary data collection methods included field surveys, structured interviews, and focus group discussions with key stakeholders, such as policymakers, transportation professionals, and local commuters. Field surveys provided quantitative data on transportation usage patterns, energy consumption, and modal choices within the city. At the same time, interviews and focus groups captured qualitative insights into the perceived infrastructure gaps, stakeholder perspectives on policy interventions, and potential solutions for enhancing sustainability. Such triangulation of data sources enables a more comprehensive understanding of the transportation landscape in Kampala, as suggested by Hendren et al. (2023), who emphasizes that mixed-methods approaches are well-suited to capturing both the "what" and the "why" behind complex social phenomena.

Secondary data were sourced from literature and public records, including historical and projected figures on energy supply, GDP, population, urbanization, infrastructure, GHG emissions, and current transit systems (Esfandi et al., 2024). Policy documents like the National Transport Master Plan, KPDP, and NDP III provided contextual information and facilitated alignment with national policy frameworks. This data foundation supports the study's comprehensive analysis of Kampala's transportation challenges and the development of sustainable solutions.

A Schwartz scenario planning approach was employed to explore potential future developments in Kampala's transportation sector (Mannucci et al., 2023). This study developed four scenarios: a business-as-usual scenario and three alternative scenarios emphasizing varying degrees of sustainability. Scenario planning is particularly relevant to transportation studies as it addresses uncertainties in policy, technology, and socioeconomic factors (Asgarpour et al., 2023).

The KAMPALA-TIMES model, a regional adaptation of the TIMES-VEDA framework, was used to analyze each scenario (Kimuli et al., 2023). This model assesses energy demand, supply dynamics, emissions, and costs, providing quantitative insights into the potential impacts of different scenarios.

A policy assessment compared the three alternative scenarios with the BAU scenario (Roelfsema et al., 2022). This assessment identifies policy gaps, explores trade-offs, and proposes actionable adjustments to foster green mobility and promote sustainable urban transportation. The findings provide insights into the feasibility of various policy measures and their potential impact on Kampala's GHG emissions, air quality, and economic development.

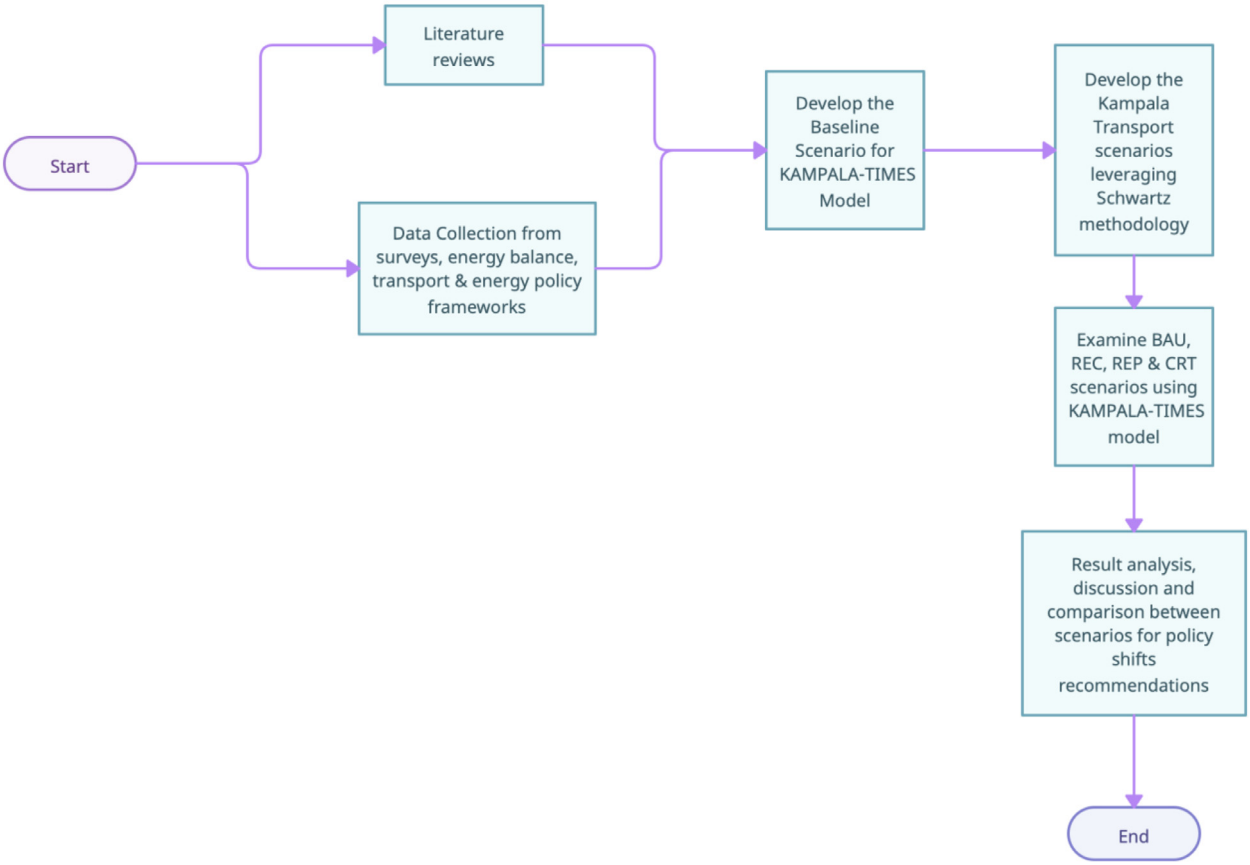

Fig. 1. Methodology flow chart

This study provides a comprehensive, evidence-based roadmap for promoting sustainable transportation in Kampala. By integrating a mixed-methods approach and the KAMPALA-TIMES model, the study offers region-specific insights and actionable recommendations, addressing the gap in existing literature. The findings empower policymakers to develop and implement sustainable, resilient, and inclusive transportation solutions.

A detailed flow chart (Fig. 1) is included to visually represent the research process, from data collection to policy recommendations. This flow chart provides a concise overview of the systematic approach used to address the research queries.

3.1. Scenarios development

This study develops four scenarios using the Schwartz scenario planning approach and analyzes them using the TIMES-VEDA model. This model assesses energy use, economic impacts, and environmental outcomes, providing insights into potential energy pathways and GHG mitigation strategies for Kampala's transportation sector (Braunreiter et al., 2021).

The Schwartz scenario planning approach allows for exploring multiple future scenarios for Kampala's transportation system, considering physical realities and operational constraints. This approach enables a comprehensive examination of potential outcomes and their feasibility (Chermack, 2022).

This study uses Peter Schwartz's rigorous six-step procedure to develop four scenarios, exploring how different policy and investment decisions might unfold under various future conditions. This scenario-based approach provides insights for policymakers and stakeholders to foster a proactive approach to sustainable urban transportation planning.

Define a focal issue;

The first phase of developing scenarios for Kampala involved articulating a core driving question that would steer the entire scenario-building process. This foundational inquiry was the central focus for understanding how different future developments could impact the city's transportation landscape. The study focused on understanding how different future developments could impact Kampala's transportation landscape. The core question was: "What strategies should be implemented to develop a sustainable urban transportation system in Kampala?"

This central question allowed the study to explore the uncertainties surrounding potential future changes and deviations from the business-as-usual trajectory. The focus at this stage of development was on identifying the inherent uncertainties within the proposed transportation system for Kampala. Significant shifts in the transportation sector—fueled by unpredictable demand growth, the absence of a comprehensive GHG emissions abatement strategy, suboptimal trip management, and systemic inefficiencies—cast substantial doubt on the practicality and sustainability of the current business-as-usual pathways. These uncertainties, coupled with the need to address critical gaps in existing policies and planning frameworks, underscored the importance of exploring three alternative scenarios diverging from the status quo.

This study uses scenario planning to understand and address uncertainties in Kampala's transportation sector, aligning with strategic foresight literature (Sunitiyoso et al., 2023). This approach helps explore future scenarios and their potential impacts on energy use, emissions, and urban mobility.

Identifying Key Drivers in the Transportation Environment;

With a well-defined focal issue and a robust investigative framework, the study proceeded to identify and categorize the fundamental drivers influencing Kampala's transportation sector. This stage was crucial in detailing the interactions and components that would inform the development of the scenarios. It provided a foundation for comprehensive analysis, bridging knowledge gaps, and ensuring a holistic understanding of the key elements shaping Kampala's transportation landscape. By incorporating various perspectives within a participatory framework, the study aimed to holistically explore multiple facets of a single focal issue. The following represents a synthesized overview of some critical factors considered in the scenario development process.

First, trip mode optimization was identified as a critical driver, encompassing the allocation and management of different transport modalities such as buses, sedans, trucks, motorbikes, and trains. Effective optimization is vital for enhancing the transportation system's efficiency and reducing overall energy consumption, aligning with studies highlighting the importance of modal integration in sustainable transport planning (Lättman & Otsuka, 2024; Mouratidis et al., 2023).

Second, the envisioned future energy-economic-environment (E3) nexus of Kampala's transportation sector emerged as a pivotal consideration. This nexus represents the complex interrelationships between energy use, economic growth, and environmental sustainability, a concept increasingly recognized in urban planning literature as essential for achieving sustainable development (Raihan et al., 2022).

Third, access to low-carbon technologies and the potential for technological advancements during the planning and implementation phases were highlighted as critical determinants of the sector's sustainability trajectory. The study recognized that technological innovation is a crucial enabler for transitioning to cleaner, more efficient transportation systems, which is in line with research that underscores the role of technological diffusion in sustainable urban mobility (Kwilinski et al., 2024).

Additionally, strategies for minimizing environmental disruptions and enhancing sustainability were examined, focusing on reducing greenhouse gas emissions and mitigating other negative environmental impacts of urban transportation. This aligns with global commitments to climate action, as articulated in the Paris Agreement and SDGs (7 & 13) (Abbasi et al., 2024).

Further, optimizing renewable energy technologies for electricity production was considered a sustainable option for promoting green mobility in Kampala. The study analyzed how renewable energy sources, such as hydro and solar, could be leveraged to power an electrified mass rapid transit system, aligning with literature that advocates for integrating renewable energy in urban transport systems to reduce carbon footprints (Kimuli et al., 2024).

Moreover, the public perception and acceptance of a mass rapid transit system with an electrified metro at its core were identified as crucial social drivers. Studies on the social dimensions of sustainable transportation have highlighted the importance of understanding public attitudes towards mass transit and electric mobility for successful implementation and uptake (Corradi et al., 2023).

Lastly, the effectiveness of current energy and transportation policies was scrutinized to identify policy gaps and opportunities for improvement. This involved evaluating existing frameworks and regulations to determine their alignment with sustainable development objectives and capacity to support a transition to a greener transportation system.

By analyzing these imperative forces, the study aimed to provide a nuanced understanding of the multifaceted dynamics influencing Kampala's transportation sector. This comprehensive approach allowed for a more informed exploration of potential future scenarios, ultimately contributing to more sustainable and resilient transportation planning for the city.

Evaluating Key Drivers by Importance and Uncertainty;

The interconnected nature of Kampala's energy, economic, and environmental transportation system resulted in a complex web of critical factors identified in the previous phase. To systematically evaluate these factors, the study focused on identifying and assessing the underlying driving forces that underpin them. This involved thoroughly examining each driving force's relative importance and the degree of uncertainty it introduces into the transportation system.

The analysis commenced by scrutinizing the driving forces of energy diversity and the prevailing dominance of fossil fuels in Kampala's mobility landscape. While fossil fuels remain the primary energy source for transportation, contributing significantly to emissions, the global shift towards cleaner energy presents an opportunity for diversification. However, this transition also introduces uncertainty regarding the pace and extent of adopting alternative fuels and technologies.

The study evaluated the importance of clean energy initiatives, considering their potential to reduce emissions, improve air quality, and enhance energy security. Clean energy initiatives, such as electrifying transport and using renewable energy sources, are crucial drivers of sustainable urban mobility. However, their implementation is fraught with uncertainties, including technological feasibility, economic viability, public acceptance, and the pace of regulatory support.

The study also explored biomass's dominance in Uganda's primary energy mix, recognizing its significant role in the national energy landscape. While biomass remains a critical energy source for many urban and rural households, its relevance to transportation is less direct. Nonetheless, biofuel potential as an alternative energy source introduces another layer of complexity and uncertainty when evaluating future transportation scenarios for Kampala.

Furthermore, the role of low-carbon electricity in transportation emerged as a pivotal uncertainty. While integrating renewable energy sources into Kampala's transport infrastructure represents a transformative opportunity, uncertainties around infrastructure development, technological advancements, and policy frameworks complicate the transition.

These critical uncertainties were identified as central themes and primary drivers of tension within the scenario narratives. The study evaluated these forces by assessing their immediate impact on the transportation system and their broader implications for urban sustainability and resilience. This comprehensive approach enabled the construction of robust and plausible future scenarios for various potential developments within Kampala's transportation sector.

Select a scenario logic;

This study's construction of scenario narratives hinged on identifying and framing key uncertainties that provided clarity and structure to the foundational themes underpinning scenario development. Each scenario was meticulously crafted to uniquely engage with these critical uncertainties, thereby delineating divergent pathways for Kampala's transportation sector. In the fourth step of the methodology, a coherent framework was established, linking the four scenarios to three fundamental questions: the prioritization of greenhouse gas (GHG) reduction, the efficacy of current transportation policies, and the primary drivers shaping Kampala's future energy and transportation landscape.

The scenario logic was designed to create a logical sequence of potential developments and decision points that could profoundly impact Kampala's transportation system. This approach ensured that each scenario represented a distinct context where various external forces, such as technological advancements, policy shifts, and global economic trends, could significantly influence the city's energy and transportation planning. By defining these alternative futures, the study sought to illuminate the possible factors that could drive change and the diverse contexts in which these transformations might occur.

At the initial point of divergence, each alternative scenario considered how external shifts, such as fluctuations in global energy markets, technological breakthroughs, or evolving geopolitical dynamics, might shape the planning process for Kampala's transportation future. These shifts were examined within an increasingly complex and insecure global order, where uncertainties about energy supply, technological capabilities, and policy directions could have profound implications for the city's transportation and energy strategies.

The scenarios were then linked to critical decision points that captured key moments of potential divergence in Kampala's energy and transportation trajectory. These decision points reflected the choices and trade-offs that policymakers and stakeholders might face in pursuing sustainable urban mobility. For instance, each scenario narrative explored decisions regarding adopting low-carbon technologies, investments in public transportation infrastructure, or prioritizing policy measures to reduce emissions and enhance sustainability.

Collectively, the scenario narratives for Kampala's transportation sector aimed to explore a broad spectrum of possible futures, examining the diverse factors that could drive change and the various contexts in which these transformations might occur. The study provided a robust foundation for analyzing potential pathways to a sustainable and resilient urban transportation system by developing a logical scenario framework grounded in the interplay of critical uncertainties and decision points. This approach facilitated a nuanced exploration of the challenges and opportunities facing Kampala's transportation sector, contributing valuable insights to the ongoing discourse on urban sustainability and resilience in rapidly growing cities.

Develop scenarios around uncertainties;

In the fifth step, detailed narratives were constructed for each scenario, exploring various facets of sustainable urban mobility and presenting plausible hypotheses for the future. They moved beyond the conventional business-as-usual approach, considering different priorities and strategies.

By focusing on the critical uncertainties identified in earlier stages, the scenarios provided a structured yet flexible framework to analyze the potential pathways for Kampala's transportation system. The narratives embraced the complexity and dynamism of urban systems, recognizing that multiple outcomes could arise depending on various variables, including policy decisions, technological advancements, and shifts in societal attitudes toward sustainability.

Each scenario narrative served as a distinct lens to examine the core issues facing Kampala's transportation sector, fostering a deeper understanding of the interdependencies between energy consumption, greenhouse gas emissions, infrastructure development, and urban planning. For example, one scenario might prioritize the rapid deployment of low-carbon technologies and investment in electrified mass transit systems. At the same time, another might focus on incremental improvements within the existing infrastructure, emphasizing energy efficiency and reduced reliance on fossil fuels.

Developing these scenarios around key uncertainties enabled the study to foster a more nuanced discourse on future pathways, encouraging stakeholders to consider a broader range of potential strategies and outcomes. This approach aligns with strategic foresight and scenario planning principles, emphasizing the importance of exploring multiple, diverse futures to enhance decision-making under uncertainty following Mannucci (2024).

Constructing these narratives, the study challenged conventional assumptions and explored alternative futures for Kampala's transportation system. This scenario-based approach identified policy gaps and opportunities, providing valuable insights for urban planners and policymakers.

Developing scenarios around uncertainties was crucial for understanding the complex factors shaping Kampala's transportation future. This approach advances sustainable urban transportation planning by providing a foundation for informed policy development and strategic planning.

Analyze and evaluate the implications of the scenarios.

In the final phase, the study comprehensively analyzed four scenarios using the TIMES-VEDA model, a bottom-up engineering tool (Schwartz, 2012; Ogilvy & Schwartz, 2004; Verity, 2003). This model translated qualitative narratives into quantifiable data to assess energy, economic, and environmental impacts.

The KAMPALA-TIMES model detailed each scenario's implications for energy consumption, greenhouse gas (GHG) emissions, and overall sustainability within Kampala's urban transportation system. By incorporating various technological, economic, and policy variables, the model facilitated an exploration of the potential trade-offs and synergies associated with each pathway. Factors such as low-carbon technology adoption rates, changes in transportation demand patterns, and the impact of infrastructure development on energy efficiency and GHG reduction were meticulously considered.

The quantitative evaluation provided a robust foundation for assessing each scenario's feasibility and effectiveness. It allowed for a deeper understanding of the transportation sector's interdependencies and aligned with recommendations from strategic scenario planning literature (Yeh et al., 2008).

This study identified the most viable pathways for reducing GHG emissions and promoting sustainable mobility in Kampala. The study provides insights into a coordinated approach to urban planning, aligning energy policies, transportation strategies, and environmental goals by analyzing the implications of various policy interventions, technological innovations, and behavioral changes.

Ultimately, evaluating the scenarios' implications was crucial in informing decision-makers about the potential outcomes of different strategic choices, fostering a proactive and informed approach to urban transportation planning in Kampala.

The study developed a baseline scenario, a Reduction in Electricity Consumption Scenario, a Renewable Electricity Portfolio Scenario, and a CO_2 Reduction Target Scenario. The baseline scenario represents business as usual, while the other three scenarios are policy-driven trajectories formulated to address the research questions under consideration.

3.1.1. The baseline scenario (BAU)

In this scenario, the trajectory of urban transportation in the Kampala Metropolis remains unchanged, reflecting a continuation of current practices and policies with limited commitment to sustainability. It is the baseline case depicting a future for the Kampala Metropolis where conventional transportation practices persist, resulting in environmental, social, and economic challenges. Sustainability considerations take a back seat, leading to a continued trajectory that does not effectively address the pressing issues of green mobility and global warming. The BAU scenario anticipates a continuation of fossil fuel dependency, inefficient transportation systems, and limited investment in low-carbon technologies and infrastructure. As such, it highlights the potential repercussions of inaction, including increased greenhouse gas (GHG) emissions, worsening air quality, and declining public health outcomes.

Furthermore, the persistence of current practices is likely to exacerbate socio-economic disparities, particularly regarding access to reliable and affordable transportation options. The BAU scenario is a cautionary tale, highlighting the limitations of maintaining the status quo. Existing literature underscores the inadequacy of such an approach in addressing urban sustainability challenges (Olabi et al., 2023). It emphasizes the urgent need for strategic policy interventions and the adoption of innovative transportation technologies to achieve meaningful progress toward sustainable development goals. The GDP growth rate is 5.8%, and the population growth rate is 3.1 % over the planning period.

3.1.2. Reduction in Electricity Consumption Scenario (Scen_REC)

The Reduction in Electricity Consumption (Scen_REC) scenario focuses on reducing overall electricity demand in the transport sector by promoting energy efficiency and modal shifts to less energy-intensive options like cycling and walking (Joseph, 2021). This approach aims to achieve a balanced approach to electrification in urban transport, mitigating potential environmental and economic impacts.

Scen_REC retains the demographic and economic assumptions of the baseline scenario but, through its focus on demand reduction, aims to achieve more sustainable energy consumption patterns while still incorporating the benefits of electrified transport. This approach aligns with research highlighting the importance of energy efficiency and diversified approaches to sustainable urban mobility (Al-Thani et al., 2022).

By integrating energy-efficient technologies, encouraging behavioral changes in urban mobility, and promoting a balanced approach to electrification, Scen_REC contributes to a broader understanding of how urban transportation systems can evolve towards a low-carbon and energy-efficient future, ensuring sustainability for Kampala's urban environment.

3.1.3. The renewable electricity portfolio scenario (Scen_REP)

The Renewable Electricity Portfolio (Scen_REP) scenario envisions a shift towards a sustainable, low-carbon energy supply for Kampala's transportation sector. It prioritizes renewable energy sources to power the electrified MRT system and other modes of transport, reducing reliance on fossil fuels and mitigating environmental and health impacts. This scenario maintains consistent demographic and economic growth projections with the baseline scenario, facilitating comparative analysis for policy design.

This emphasis on renewable energy integration aligns with global trends and research advocating sustainable energy transitions (Hassan et al., 2024; Tian et al., 2023). The Scen_REP scenario offers insights for policymakers and stakeholders committed to sustainable urban development.

3.1.4. CO_2 reduction targets scenario (Scen_CRT)

The CO_2 Reduction Targets Scenario (Scen_CRT) mandates a stringent, linear reduction in transportation-related CO_2 emissions. By the end of the planning period, the baseline estimates will be curtailed by 85%, aligning with international and national climate goals. This scenario aims to overhaul the existing transportation system and significantly reduce the city's carbon footprint.

Scen_CRT envisions a future underpinned by clean energy technologies, enhanced fuel efficiency, modal shifts, and robust public transportation systems (Alipour & Dia, 2023). This scenario mandates a stringent reduction in CO2 emissions, aligning with international and national climate goals.

Consistent demographic and economic variables with the baseline case allow a precise analysis of the scenario's environmental and policy impacts. Scen_CRT provides a clear framework for achieving substantial carbon reduction and fostering sustainable urban development in Kampala.

This scenario positions Kampala at the forefront of climate action, setting a precedent for other regional cities. By focusing on energy efficiency, clean energy deployment, and sustainable urban transport planning, Scen_CRT offers a comprehensive blueprint for decarbonizing urban transport, aligning with global best practices (Razmjoo et al., 2022). Ultimately, it lays the groundwork for a resilient, low-carbon urban future, offering invaluable insights for stakeholders committed to sustainable development.

3.2. Projection of the demand component of the baseline scenario

The baseline scenario's demand projection employs an energy-elasticity model to forecast future energy consumption and carbon emissions in the transportation sector (Edelenbosch et al., 2017).

This baseline projection is a crucial benchmark for evaluating the potential impacts of policies and interventions promoting sustainable transportation. It provides the exogenous input into TIMES-VEDA for quantifying the energy impacts associated with the baseline trajectory, highlighting the scale and scope of changes required to achieve sustainability goals.

This baseline provides a benchmark for evaluating the impacts of sustainable transportation policies and interventions. The KAMPALA-TIMES model expresses transportation demand in energy units, VKT, PKM, and TKM, offering a comprehensive view of Kampala's transportation energy landscape. This enables the exploration of various policy levers and technological pathways to promote sustainable urban mobility.

3.3. KAMPALA-TIMES model: a specialized application of the TIMES-VEDA framework for Kampala's sustainable urban mobility

The KAMPALA-TIMES model, employed in this study, is a specialized adaptation of the TIMES-VEDA (Versatile Data Analyst) framework, initially developed by the International Energy Agency (IEA). This model is pivotal for analyzing sustainable transportation policy design within Kampala's urban context. The TIMES-VEDA model is renowned for its robust, bottom-up linear optimization

capabilities, allowing for a detailed examination of energy systems' energy, economic, and environmental aspects. It effectively integrates analyses across energy supply, transformation, and demand technologies within various sectors, making it an invaluable tool for comprehensive energy system analysis (Kimuli et al., 2024).

Tailored specifically for Kampala, the KAMPALA-TIMES model facilitates an in-depth evaluation of greenhouse gas (GHG) abatement strategies and explores the complex interactions within the city's energy system, focusing on transportation demand. This focus is crucial for fostering green mobility initiatives within the metropolis. The model's comprehensive data integration—spanning existing energy balances, transportation infrastructures, and demographic trends—creates a solid foundation for developing a multimodal transportation system anchored with an electrified Mass Rapid Transit (MRT) system and projecting GHG emissions and their mitigation strategies.

The TIMES-VEDA model was selected for this research because it can provide a detailed sectoral analysis, which is essential for developing nuanced transportation policies. Furthermore, its compatibility with the Schwartz scenario planning technique enriches this study by incorporating a strategic foresight method that helps visualize multiple plausible futures and understand their implications for urban mobility and policy-making, as supported by Sunitiyoso et al. (2023) in their review of scenario methods.

Moreover, the TIMES-VEDA framework's strength lies in its comprehensive approach to modeling the entire transportation sector, including passenger and freight dimensions across various modalities. This level of detail is critical for understanding the potential impacts of diverse policy interventions on Kampala's transportation landscape.

Internally, the KAMPALA-TIMES model is structured with interconnected modules, including an energy supply mix module, a power production module, five demand modules for the critical sectors, and specialized demand compartments for land passenger and freight transportation in the transportation module. This modular approach allows for an extensive examination of different transportation modes and their corresponding technologies and carbon emissions, ranging from conventional fossil-fuel systems to emerging innovations like hybrid vehicles and fully electrified MRT systems.

The technological and economic attributes of the model, as well as its GHG emission coefficients, are meticulously derived from validated datasets within the TIMES-VEDA framework, ensuring that the study's outcomes are both empirically robust and reflective of contemporary trends.

Thus, the KAMPALA-TIMES model is an essential analytical tool for policymakers and urban planners. It offers insights that support the development of sustainable and context-specific transportation solutions for Kampala. Integrating this model with Schwartz scenario planning provides a robust methodological foundation for this study. It aligns with global sustainability goals and facilitates strategic urban transportation planning that is aware of both current needs and future challenges.

4. Analysis and discussion of the model results

The KAMPALA-TIMES model provides critical insights for developing a sustainable urban transportation plan for the Kampala Metropolis. The ensuing analysis and discussion delve into the model's freight and passenger transportation projections, encompassing key dimensions such as supply energy, electricity generation by fuel type, trip mode, energy demand, carbon emissions, system expenditures, and the influence of policy interventions over the planning horizon.

4.1. Kampala supply energy

The analysis shows that fossil oil consumption is organically expanding, with an average growth rate of fourfold for the Business as Usual (BAU), Reduction in Electricity Consumption (REC), and Renewable Electricity Portfolio (REP) scenarios, mirroring the city's escalating mobility demands (Figs. 2 and 3). However, in the Carbon Reduction Target (CRT) scenario, the demand for fossil oils doubles by the end of the planning period. This trend underscores the persistent reliance on fossil fuels to meet transportation needs, highlighting the imperative for sustainable alternatives and strategies to mitigate environmental impacts. Furthermore, global trends corroborate these findings. Studies by Ghorbani et al. (2023) and Tian et al. (2023) highlight the widespread dependence on fossil fuels within the transportation sector, underscoring the urgent need for comprehensive energy transition plans that prioritize sustainable modes of transport and the adoption of cleaner fuels.

The persistent reliance on fossil fuels underscores the need for comprehensive energy policies, such as establishing an electrified MRT system, to encourage a modal shift towards cleaner and more efficient transportation options. This aligns with global research advocating electrified public transport as a critical strategy for achieving low-carbon urban mobility (Miraftabzadeh et al., 2024; Liu et al., 2023).

The analysis reveals that biomass constitutes the dominant energy source within the metropolitan energy mix, initially accounting for 52.4% of total consumption. The projected growth of biofuels, averaging 36% across the four scenarios, underscores their increasing significance in pursuing sustainable energy solutions. However, the rapid growth rates projected for charcoal, a processed form of woody biomass, ranging from 55% to 74%, highlight the urgent need to implement sustainable production and consumption practices to mitigate potential environmental and health impacts. This finding aligns with research by Forfora et al. (2024) and Makepa et al. (2024), underscoring the significant ecological implications of biomass utilization, particularly about carbon emissions and deforestation. The study advocates integrating user-friendly, efficient, low-emission, small-scale biomass technologies into the broader energy mix. While decarbonizing the transportation sector is crucial, more is needed to achieve holistic sustainability within the city's energy system. Therefore, incorporating these technologies can offer a complementary pathway to reduce emissions further and promote energy access, particularly in contexts where biomass remains a household's primary energy source. Research by Creutzig et al. (2024) and Arent et al. (2022) advocate for a holistic approach to achieving a sustainable urban energy system,

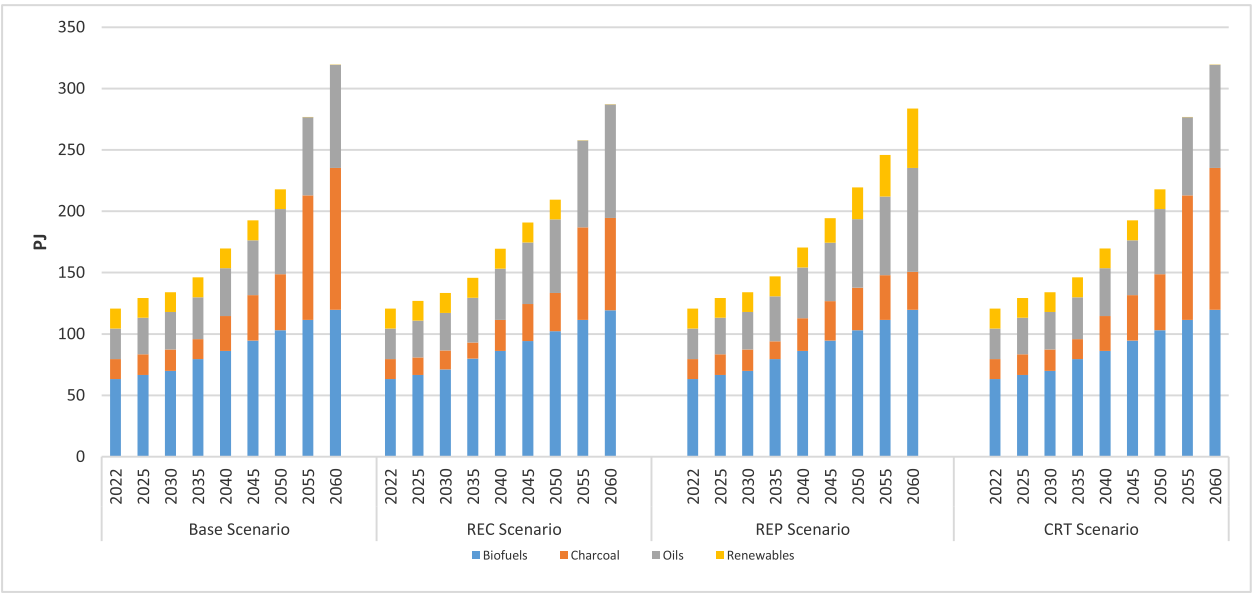

Fig. 2. Total primary energy supply- four scenarios (PJ)

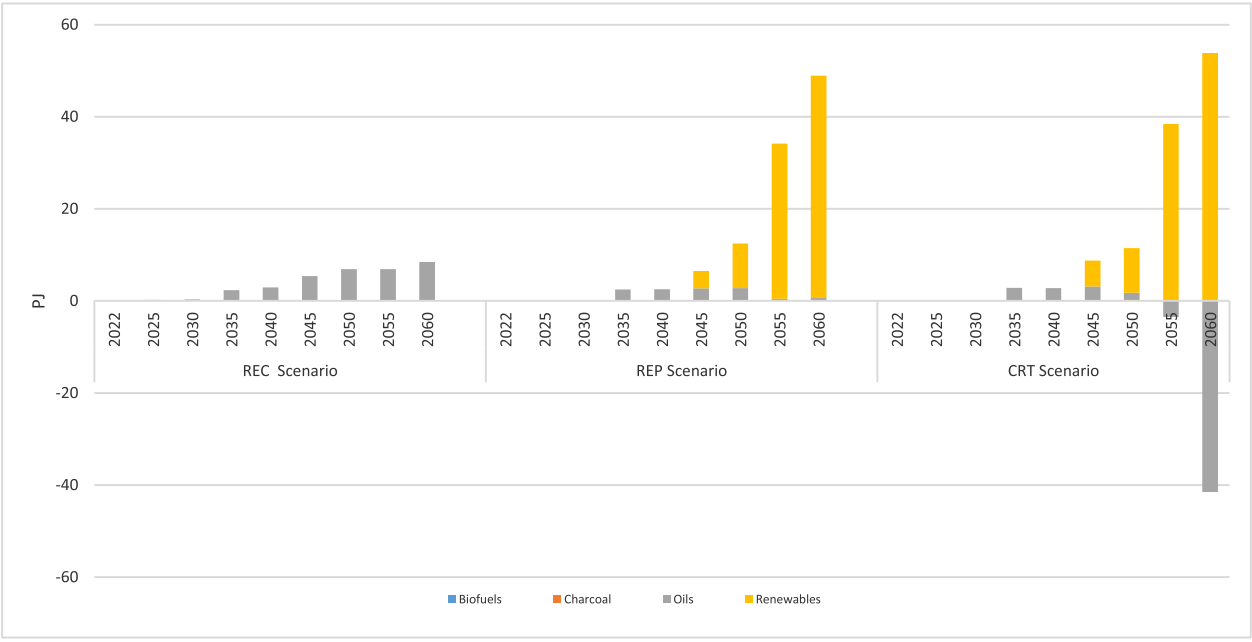

Fig. 3. Kampala supply energy- difference from the BAU scenario (PJ)

emphasizing implementing carbon abatement strategies across all vital energy demand sectors, including transportation, households, commercial buildings, industry, and agriculture.

The study advocates for enacting and enforcing stringent legislation to combat indiscriminate tree felling. It recognizes the critical role of forest conservation in mitigating climate change and ensuring sustainable biomass availability. Furthermore, it underscores the importance of allocating adequate research funding to advance sustainable biochar production technologies, which can offer a cleaner and more efficient alternative to traditional biomass fuels.

The research highlights the need for sufficient resource allocation for forest management practices, transitioning from woody biomass to low-carbon alternatives (Rial, 2024; Elkhatat & Al-Muhtaseb, 2024), and prioritizing renewable energy sources and their efficient utilization in transportation (Teixeira Dias et al., 2023; Kabeyi et al., 2022). This approach aligns with sustainable development goals and ensures a resilient urban future for Kampala.

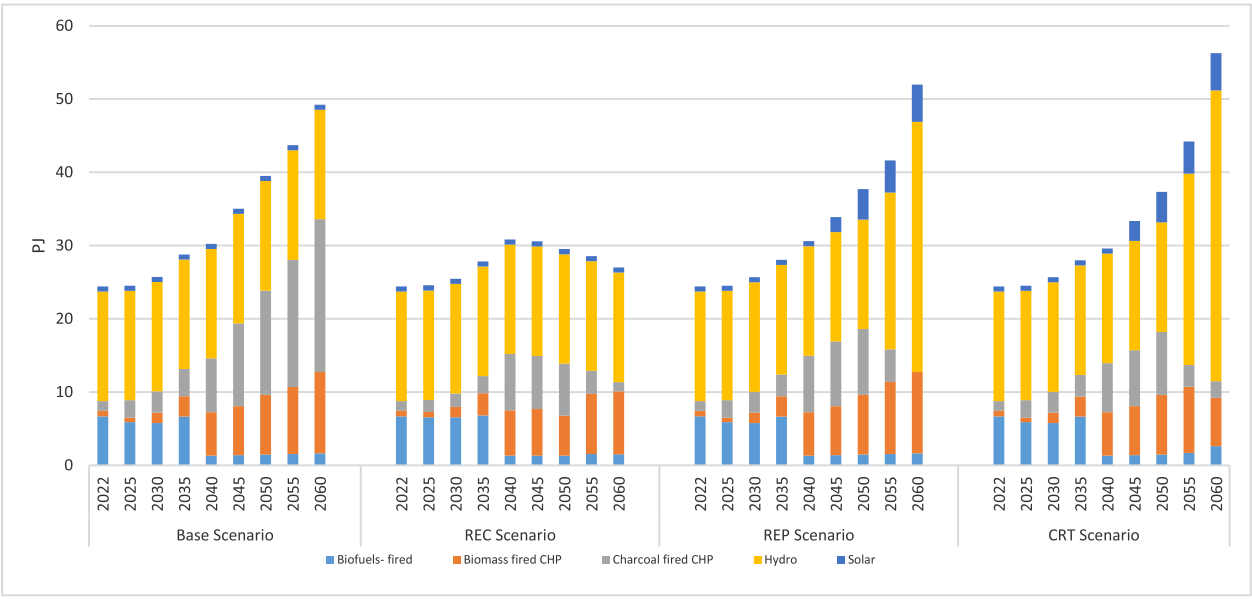

Fig. 4. Power production by fuel type- four scenarios (PJ)

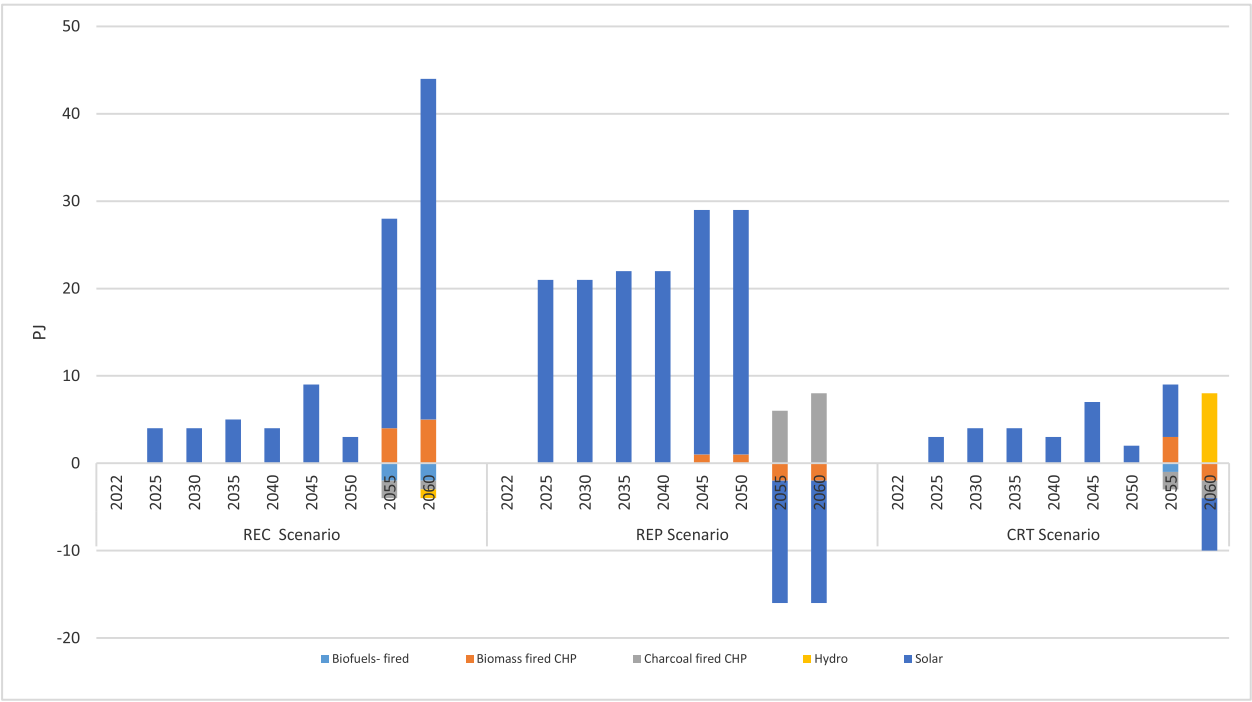

Fig. 5. Power production by fuel type- difference from the BAU scenario (PJ)

4.2. Power Production by Fuel Type (PJ)

The KAMPALA-TIMES model analysis identifies hydropower as the cornerstone of sustainable electricity generation for future transportation scenarios in Kampala (Figs. 4 and 5). This aligns with global best practices advocated by Vargas-Ferrer et al. (2022) and Chu et al. (2022), which emphasize the role of hydropower in achieving a balanced and low-carbon energy mix. The Reduction in Electricity Consumption (REC) scenario, constrained by a focus on minimizing energy use, underscores the need for a nuanced approach to energy management that balances conservation with the growing demands of urbanization and economic development.

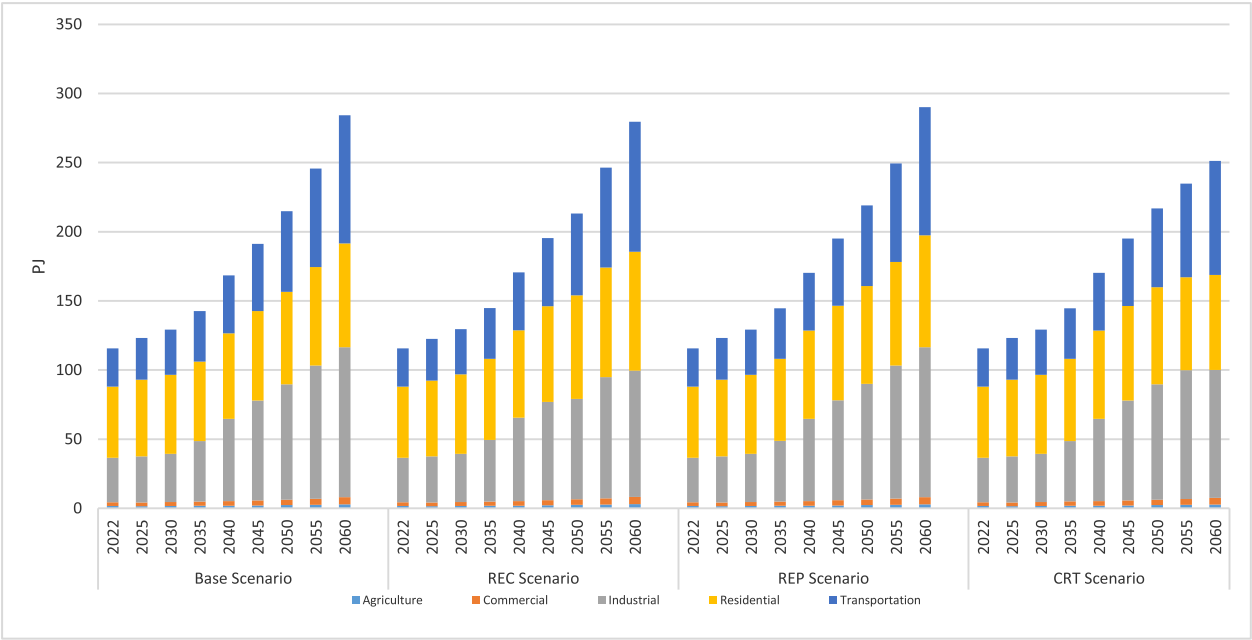

Fig. 6. Final energy consumption by sector – four scenarios (PJ)

While biomass-fired Combined Heat and Power (CHP) plants remain significant contributors throughout the planning period, the study emphasizes the imperative of scaling up photovoltaic (PV) solar power generation to complement hydropower for long-term sustainability. The Renewable Electricity Portfolio (REP) and REC scenarios demonstrate the potential of diversified energy sources to enhance system resilience and efficiency, echoing findings from Lv H et al. (2024). Notably, the Carbon Reduction Target (CRT) scenario surpasses the baseline by doubling PV-solar energy production, even at increased system expenditures. Numerous studies support this strategic investment in solar energy, highlighting its potential for cost-effective and sustainable power generation in regions with abundant solar resources, such as Kampala (Kumar et al., 2023; Yu et al., 2022).

The model analysis strongly advocates adopting the CRT scenario, which promotes a diversified energy mix emphasizing renewable sources to achieve the most sustainable power generation solution. This approach facilitates realizing an electrified mass rapid transit (MRT) system with a Kampala metro at its core, a cornerstone of the metropolis' greener, more sustainable transportation future. The transition toward renewable energy sources aligns with global trends and best practices for decarbonization and is essential for achieving long-term environmental and economic sustainability in rapidly urbanizing regions (Hassan et al., 2024; Elavarasan et al., 2022). This is also in line with NDPIII and the Uganda Vision 2040.

4.3. Energy consumption by economic sector (PJ)

The KAMPALA-TIMES model analysis provides valuable insights into energy consumption trends across various sectors in Kampala, offering a critical foundation for evidence-based policy development. Baseline projections anticipate a substantial increase in total energy demand, rising from 115.7 Petajoules (PJ) to 284.3 PJ, reflecting the city's rapid urbanization and economic growth. However, the Carbon Reduction Target (CRT) scenario, which emphasizes sustainable energy practices and carbon abatement measures, presents a more promising trajectory, with a projected final demand of 251.2 PJ by 2060 (Figs. 6 and 7). This suggests that strategic policy interventions and technological advancements can effectively mitigate the growth in energy demand while supporting sustainable development.

The study further identifies the industrial sector as the dominant final energy consumer, with a projected growth of 85% across all scenarios. This finding aligns with previous research highlighting the industrial sector's significant energy consumption in urban settings, driven by manufacturing and processing activities (Elavarasan et al., 2023). The transportation sector also emerges as a key contributor, accounting for 30.1% of total energy demand, underscoring its critical role in shaping Kampala's energy landscape.

These insights highlight the imperative for targeted policy interventions to promote energy efficiency and sustainable practices within these sectors. The industrial sector, in particular, presents a significant opportunity for energy conservation and the adoption of cleaner technologies. Simultaneously, the transportation sector must focus on sustainable mobility solutions and integrating low-carbon fuels. By addressing these key sectors, policymakers can effectively manage energy demand and promote a more sustainable and resilient energy future for Kampala.

This analysis highlights the urgency of a strategic shift in energy consumption patterns to achieve sustainability. The REC and CRT scenarios forecast a decline in energy demand for the transportation and industrial sectors, aligning with Zhang et al.'s (2024) rec-

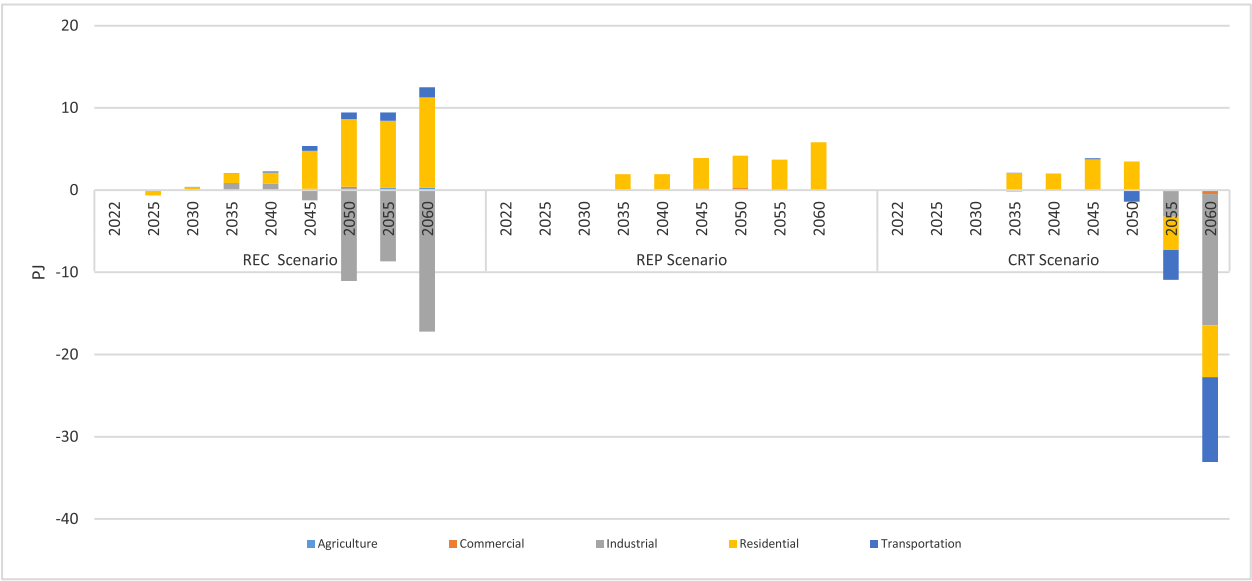

Fig. 7. Final energy consumption by sector- difference from the BAU scenario (PJ)

ommendations for sustainable energy transitions. This shift towards renewable energy and energy efficiency is crucial for aligning Kampala's growth with global sustainability objectives, the NDPIII and the Uganda Vision 2040.

Based on the study's comprehensive analysis, the Carbon Reduction Target (CRT) scenario is the most viable option for achieving sustainable energy outcomes in Kampala. The CRT scenario demonstrates lower overall energy consumption and presents a promising pathway for establishing a sustainable transportation system in the metropolis. Implementing this scenario, emphasizing the development of an electrified Mass Rapid Transit (MRT) system anchored by a metro, would enable Kampala to effectively balance its economic growth and mobility needs without compromising environmental integrity.

This approach aligns with the principles of sustainable urban development, as advocated by numerous scholars and international organizations (Wehbi, 2024). The integration of electrified mass transit systems has been shown to significantly reduce carbon emissions, improve air quality, and enhance the overall livability of urban areas (Monteiro et al., 2024; Nawazish Ali et al., 2024). Furthermore, the CRT scenario's emphasis on energy efficiency and renewable energy integration fosters a resilient and sustainable energy system that can support Kampala's continued growth while mitigating its environmental impact.

By prioritizing the CRT scenario, Kampala can exemplify a forward-looking strategy prioritizing sustainable urban development in energy planning. This will ensure its residents a cleaner, healthier, and more prosperous future.

4.4. The demand for fuel in the transportation sector (PJ)

The KAMPALA-TIMES model analysis offers valuable insights into fuel consumption patterns for various transportation scenarios in Kampala. While the Business as Usual (BAU), Reduction in Electricity Consumption (REC), and Renewable Electricity Portfolio (REP) scenarios project a rise in fuel demand (27.47PJ to 93PJ), the Carbon Reduction Target (CRT) scenario presents a compelling alternative. This scenario achieves a lower peak demand of 79.64PJ over the planning period, demonstrating the effectiveness of the CRT's focus on conservation and efficiency strategies within its technological framework (Figs. 8 and 9).

The CRT scenario's approach aligns with global sustainability objectives, as outlined in frameworks such as the United Nations' SDGs and the Paris Agreement on Climate Change. It emphasizes the critical need for a strategic shift from fossil fuel dependence towards renewable energy sources and improved energy efficiency. By incorporating these elements, the CRT scenario effectively reduces fuel consumption and associated emissions, mitigating environmental impacts while supporting sustainable urban development. This trajectory underscores the pivotal role of proactive policy interventions and technological advancements in facilitating a sustainable transportation future for Kampala.

The CRT scenario's focus on renewable energy and energy efficiency resonates with global trends and best practices in sustainable transportation planning (Kiviluoto et al., 2022). Studies such as Okoh & Onuoha (2024) and Shahzad & Cheema (2024) emphasized decarbonizing the transport sector through the increased adoption of electric vehicles, renewable energy integration, and improved energy efficiency measures. Similarly, research by O'Regan & Nyhan (2023) highlights the potential of sustainable transport systems to reduce greenhouse gas emissions, improve air quality, and enhance the overall livability of urban areas.

The CRT scenario's emphasis on sustainable transportation solutions offers a promising pathway to achieving significant carbon reduction and promoting a healthier and more resilient urban environment. By embracing this strategic approach, Kampala can

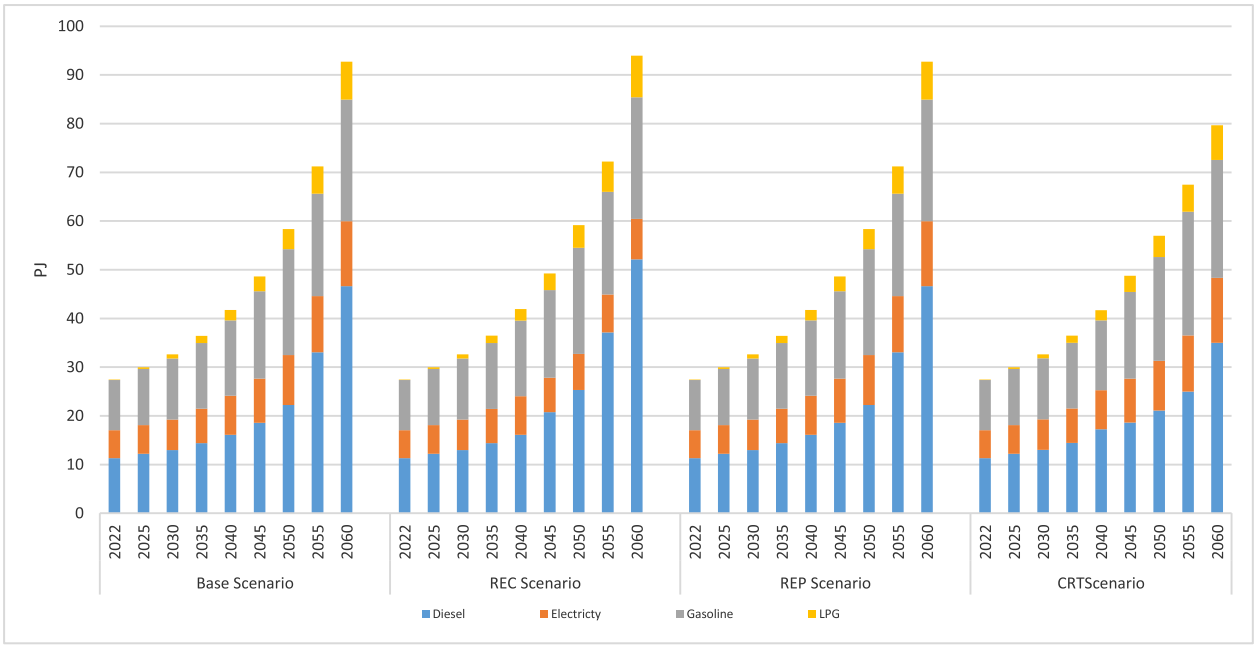

Fig. 8. Fuel consumption by transportation- four scenarios (PJ)

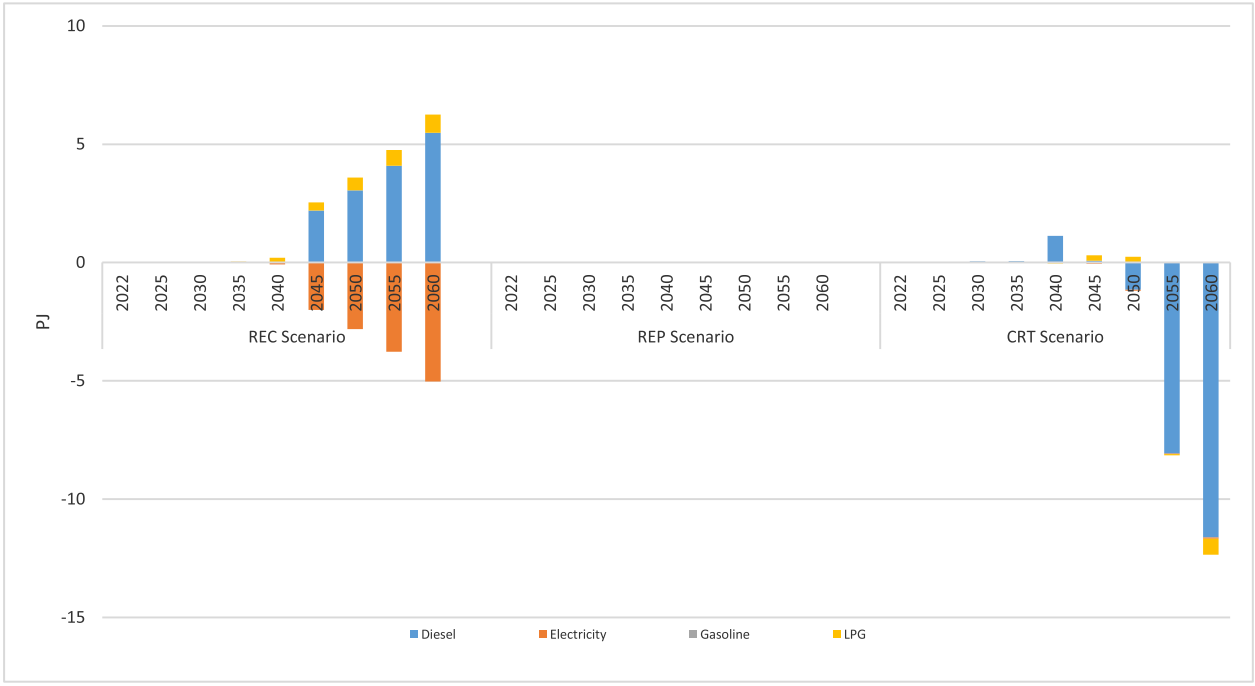

Fig. 9. Fuel consumption by transportation- difference from the BAU scenario (PJ)

position itself as a leader in sustainable urban development and demonstrate the feasibility and benefits of integrating renewable energy and energy efficiency into its transportation system.

Diesel remains the dominant fuel across all scenarios, accounting for roughly 50% of total fuel use. This fuel is primarily designated for commercial trucks, heavy short-haul trucks, and, notably, 65% of the buses operating within the mass rapid transit system in areas lacking access to the electrical grid. This persistent reliance on diesel, a significant source of greenhouse gas emissions and air pollution, underscores the critical need for expanding electrification efforts across the entire metropolitan network.

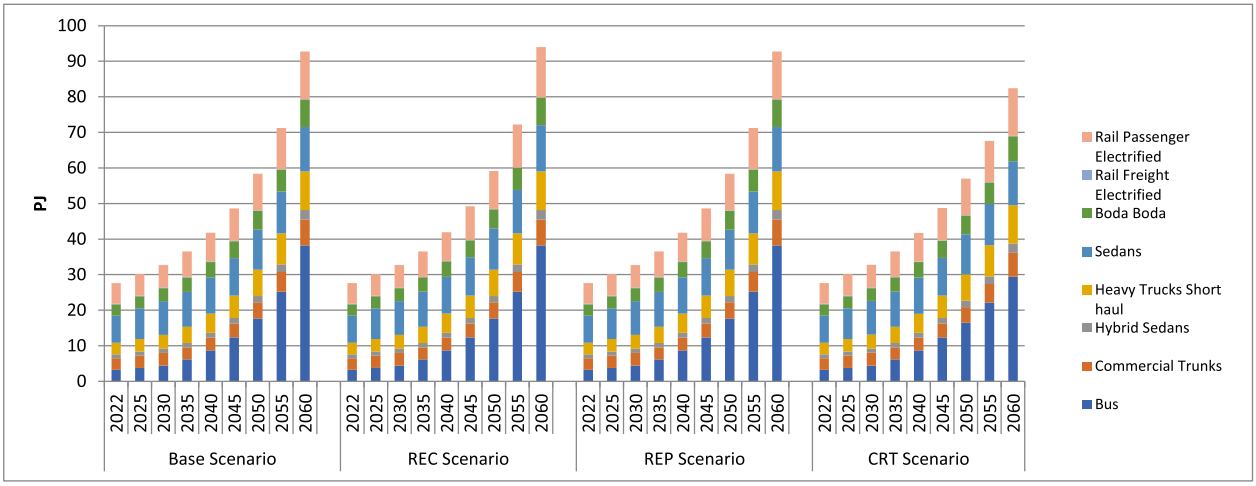

Fig. 10. Final energy demand by trip mode- four scenarios (PJ)

The continued prominence of diesel in the transportation sector aligns with observations in other developing cities, where diesel-powered vehicles often dominate due to their perceived affordability and robustness (Saurabh & Majumdar, 2023). However, the environmental and health impacts of diesel emissions necessitate a strategic shift towards cleaner alternatives (Julio et al., 2022).

The analysis underscores the crucial role of electricity in achieving a sustainable transportation future for Kampala. In all scenarios, electricity maintains a consistent presence, albeit at varying levels, facilitating the development of the envisioned electrified mass rapid transit system with a metro at its core. This transition towards electric mobility is supported by a growing body of literature highlighting the potential of electric vehicles and electrified public transport systems to reduce greenhouse gas emissions and improve urban air quality significantly (Mousavinezhad et al., 2024; Ercan et al., 2022).

The findings emphasize the need for a comprehensive approach to decarbonizing the transportation sector in Kampala. While expanding the electrical grid and promoting the adoption of electric vehicles are crucial steps, addressing the reliance on diesel in areas without grid access remains a significant challenge. This may require innovative solutions, such as deploying hybrid or renewable energy-powered buses or accelerated electrical grid expansion to ensure comprehensive electrification of the mass rapid transit system.

The CRT scenario offers the most promising path forward. Compared to the other three scenarios, it significantly reduces diesel consumption (11.6 PJ). This scenario promotes fuel efficiency and conservation, develops an electrified mass rapid transit system, and balances economic growth with environmental impact.

4.5. Final energy demand by trip mode

The KAMPALA-TIMES model provides valuable insights into the evolving energy demands associated with various transportation modes in Kampala across different scenarios. While the overall final transportation energy demand increases in all scenarios (ranging from 27.64 PJ to 93.96 PJ), the model highlights critical trends that can inform the promotion of greener mobility (Figs. 10 and 11). Commuter buses, envisaged as a pivotal element of the proposed mass rapid transit system, emerge as the most significant final energy consumer by trip mode across all scenarios. This reflects their crucial role in accommodating the city's growing demand for public transportation as it transitions towards sustainable practices. The prominence of buses aligns with observations from other rapidly urbanizing cities in developing countries, where bus systems often serve as the primary mode of mass transit (Mahmoudi et al., 2024; Mwesigwa et al., 2024).

Furthermore, the analysis underscores the significance of the proposed electrified metro (Rail Passenger electrified) as the second-highest energy consumer in all scenarios. This is attributed to its planned function as the high-capacity backbone of the city's mass rapid transit system, serving as the primary mode of passenger movement within the central business district (CBD). The emphasis on electrified rail aligns with global trends toward sustainable urban transport solutions, as evidenced by the increasing adoption of metro systems in major cities worldwide (Nawazish Ali et al., 2024; Gharehbaghi et al., 2023).

These findings emphasize the need for a balanced approach to transportation planning in Kampala. While expanding and electrifying the bus fleet is crucial for improving public transport accessibility and reducing emissions, developing an electrified metro system is equally essential for providing a high-capacity, low-carbon backbone for the city's mass transit network. By prioritizing these sustainable transportation modes, Kampala can effectively address its growing mobility needs while mitigating environmental impacts and contributing to a more livable and sustainable urban environment.

Interestingly, the study highlights the emergence of hybrid sedans as crucial players in the transition towards sustainable road transportation in Kampala. Their increasing presence signifies a positive shift towards greener mobility options, reflecting a growing awareness among consumers of the environmental and economic benefits of hybrid vehicles. However, the analysis also reveals a

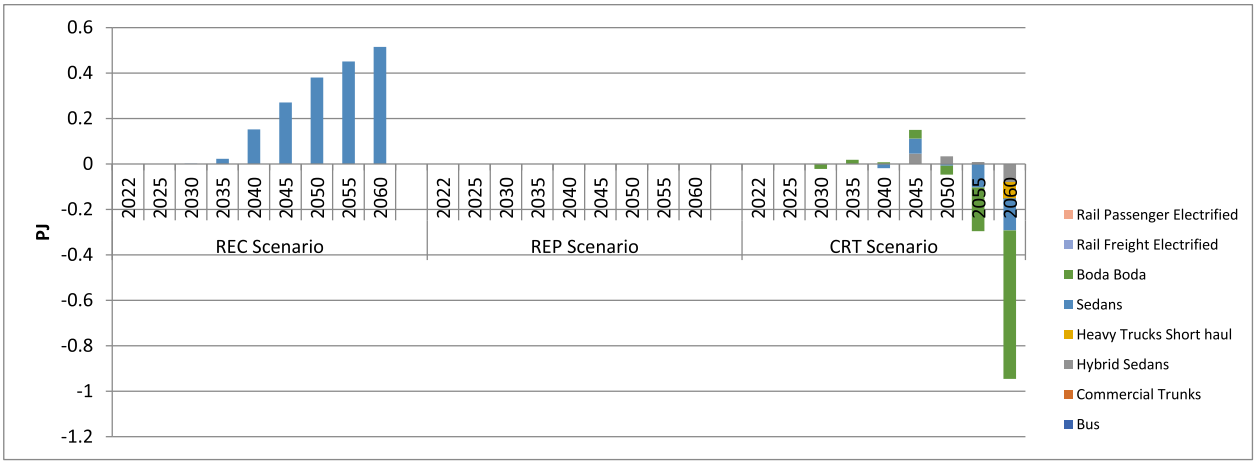

Fig. 11. Final energy demand by trip mode- difference from the BAU scenario (PJ)

concerning trend - a projected doubling of energy consumption associated with Boda-bodas (motorcycles) across all scenarios. This suggests a potential consumer preference for Boda-bodas for short trips, particularly within the Central Business District (CBD), which, if left unchecked, could undermine broader sustainability efforts.

While commercial trucks remain the dominant mode of freight transportation, achieving long-term sustainability necessitates a strategic adjustment in modal preferences. This includes a gradual shift from commercial trucks to electrified locomotives for freight transport, a transition from Kampala sedans powered by internal combustion engines to hybrid sedans for personal mobility, and a significant reduction in the reliance on Boda-bodas, particularly for short trips within the CBD. This modal shift aligns with recommendations from the literature, which emphasizes the importance of promoting public transport and non-motorized transport options to reduce congestion and emissions in urban areas (Mansoor et al., 2022; Das et al., 2022).

Furthermore, the projected increase in hybrid sedan usage underscores the potential for cleaner vehicle technologies to contribute to sustainable transportation in Kampala. This aligns with global trends towards the electrification of the transport sector, as evidenced by the increasing adoption of hybrid and electric vehicles in many cities worldwide (Shui et al., 2024). However, the challenge of addressing the rising popularity of Boda-bodas remains. Policy interventions promoting safer and more sustainable alternatives, such as electric bicycles or improved public transport options, may be necessary to curb their environmental impact and ensure Kampala's balanced and sustainable transportation future.

The model demonstrates that green mobility is a realistic possibility for Kampala, particularly under the Carbon Reduction Target (CRT) scenario. Focusing on fuel efficiency and mode shifts, this scenario promotes commuter buses and a modern electrified metro system while encouraging the adoption of hybrid sedans and potentially discouraging reliance on Boda-bodas in the passenger land category. Kampala can achieve green mobility over the planning horizon by promoting a multimodal transportation strategy.

4.6. Carbon emissions by economic sectors

The KAMPALA-TIMES model analysis provides crucial insights into Kampala's carbon emissions trajectory across various economic sectors under different scenarios (Figs. 12 & 13). While the baseline case projects a substantial increase in emissions, rising from 3.47 $MtCO_2e$ to 17.07 $MtCO_2e$, the alternative scenarios demonstrate promising pathways toward sustainability. The significant reductions in carbon emissions observed in the Reduction in Electricity Consumption (REC) scenario (13.97 $MtCO_2e$), Renewable Electricity Portfolio (REP) scenario (9.16 $MtCO_2e$), and most notably, the Carbon Reduction Target (CRT) scenario (5.89 $MtCO_2e$), highlight the effectiveness of the deployed mitigation technologies within the model.

The analysis further identifies the transportation sector as the primary contributor to carbon emissions, followed by the industrial sector and power production from Biomass-fired CHP plants. This aligns with global trends and research findings highlighting the transportation sector's significant carbon footprint, particularly in rapidly urbanizing areas with increasing reliance on fossil fuel-powered vehicles (Shahzad & Cheema, 2024; Kumar & Sharma, 2024). The substantial emissions from the industrial sector also underscore the need for energy efficiency improvements and the adoption of cleaner technologies in this sector, following Gorina et al. 2024, Tao et al. 2024, and Panjaitan et al. 2023.

Biomass-fired CHP plants' contribution to emissions emphasizes the importance of transitioning towards cleaner energy sources for power generation. While CHP plants offer potential benefits in terms of energy efficiency, their reliance on biomass can lead to significant emissions, mainly if the biomass is not sourced sustainably. This finding supports the need for policies that promote the integration of more hydropower and solar PV into the power generation mix.

The study presents a compelling argument for adopting an electrified mass rapid transit (MRT) system with a metro at its core as a pivotal strategy for decarbonizing Kampala's transportation sector. The analysis indicates a substantial reduction (47.5%) in inherent transportation carbon emissions through electricity utilization in the MRT system. This finding aligns with a growing body

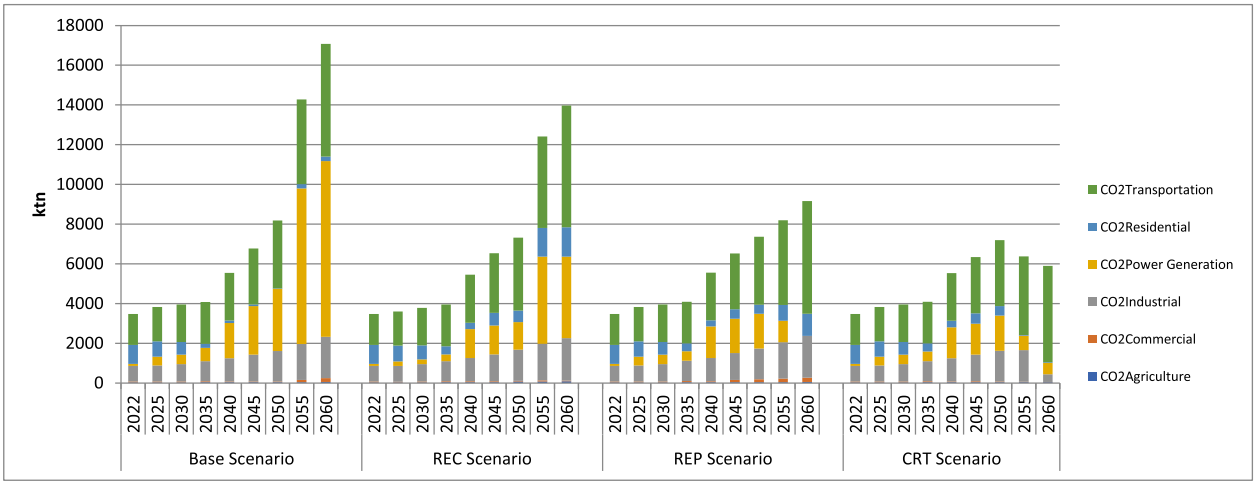

Fig. 12. CO_2 emissions by economic sector- four scenarios (ktn)

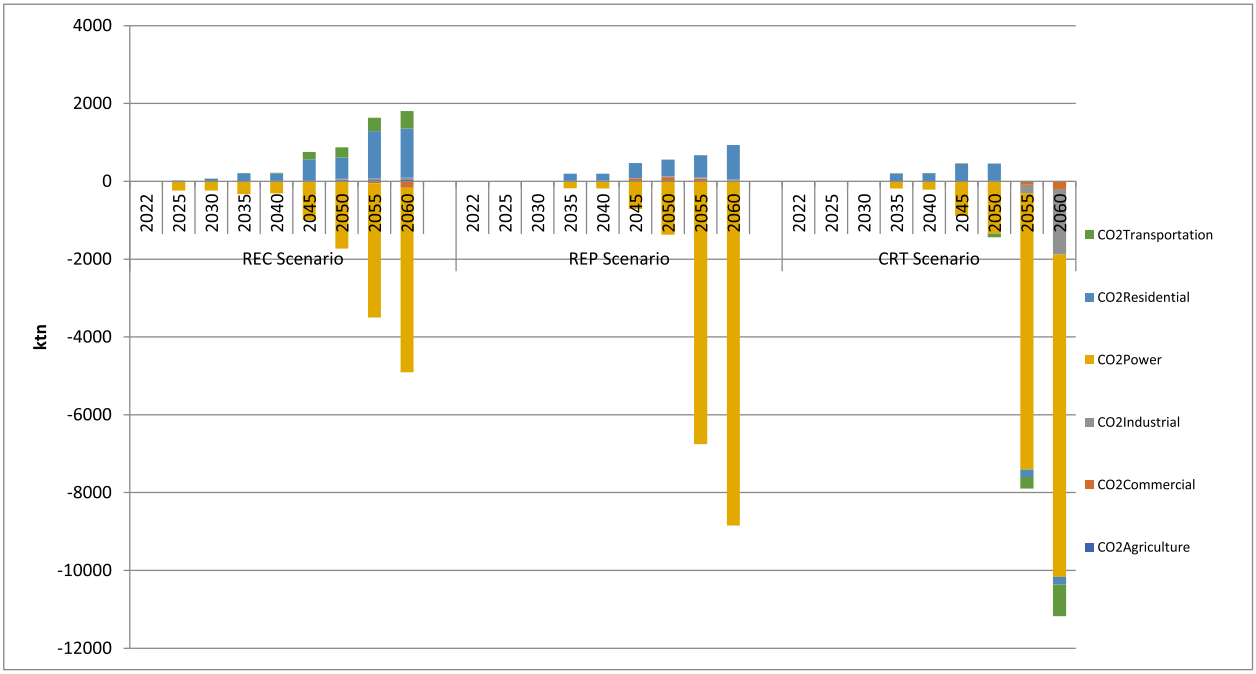

Fig. 13. CO_2 emissions by economic sector- difference from the BAU Scenario (ktn)

of literature highlighting the potential of electrified public transportation systems to reduce greenhouse gas emissions and improve urban air quality significantly (Mousavinezhad et al., 2024; Ercan et al., 2022). These results strongly support the role of an electrified metro in achieving greener mobility for the city, contributing to a more sustainable and livable urban environment.

The CRT scenario prioritizes low-carbon electricity and an electrified MRT system and emerges as the most promising pathway for Kampala's sustainable development. This approach balances economic growth and environmental impact, aligning with sustainable urban development principles.

Furthermore, the CRT scenario's emphasis on electrified mass transit aligns with global trends and best practices for achieving sustainable transportation systems (Kouridis & Vlachokostas, 2022; Lefevre et al., 2021; Lah et al., 2019). The KAMPALA-TIMES model demonstrates the transformative potential of electrified mass transit in shaping a more sustainable and resilient transportation future for Kampala.

Overall, the KAMPALA-TIMES model analysis provides a valuable framework for understanding the dynamics of carbon emissions in the metropolis and identifying key sectors and technologies for targeted mitigation efforts. This analysis paves the way for Kampala's more resilient and environmentally responsible future.

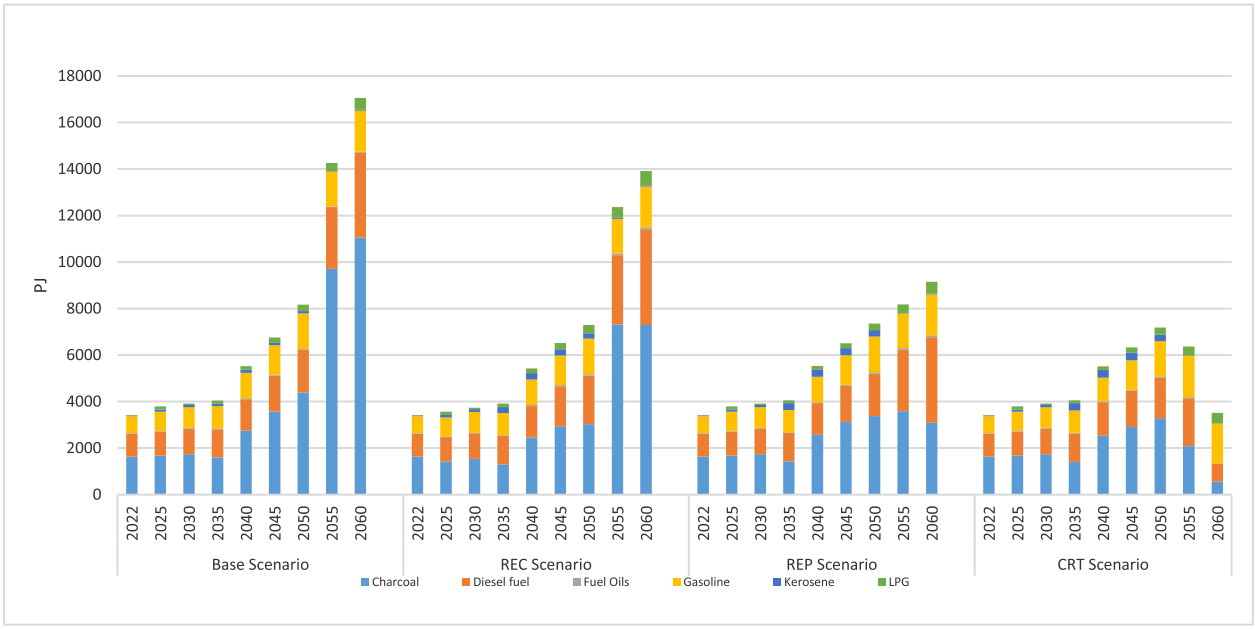

Fig. 14. CO_2 emissions by fuel- four scenarios (ktn)

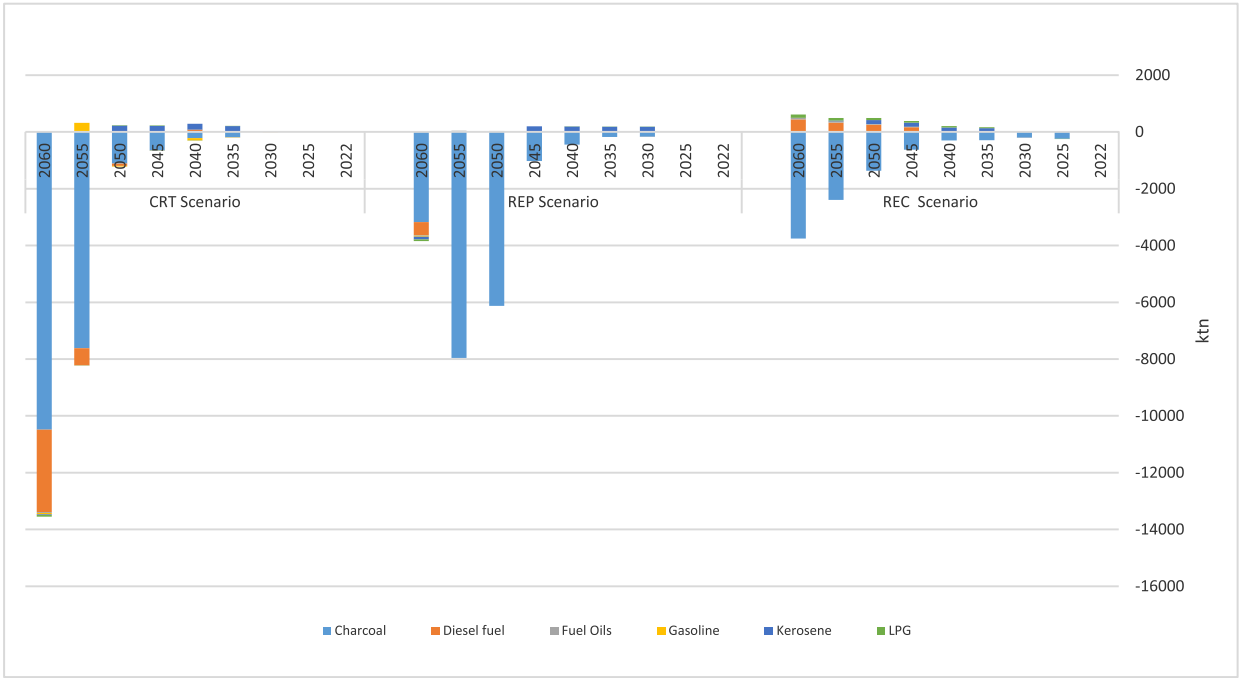

Table 15: CO_2 Emissions by Fuel- Difference from the BAU Scenario (ktn)

Fig. 15. CO_2 Emissions by fuel- difference from the BAU scenario (ktn)

4.7. Carbon emissions by Fuel Type

The analysis of the research findings, as presented in Figs. 14 and 15, offers valuable insights into the carbon emissions associated with various fuel types in Kampala across the different scenarios. While the reference scenario (BAU) projects a substantial increase in emissions, rising from 3.42 $MtCO_2e$ to 17.1 $MtCO_2e$, the alternative scenarios demonstrate promising pathways towards a more sustainable future. The significant reductions in carbon emissions observed by the end of the planning period under the Reduction

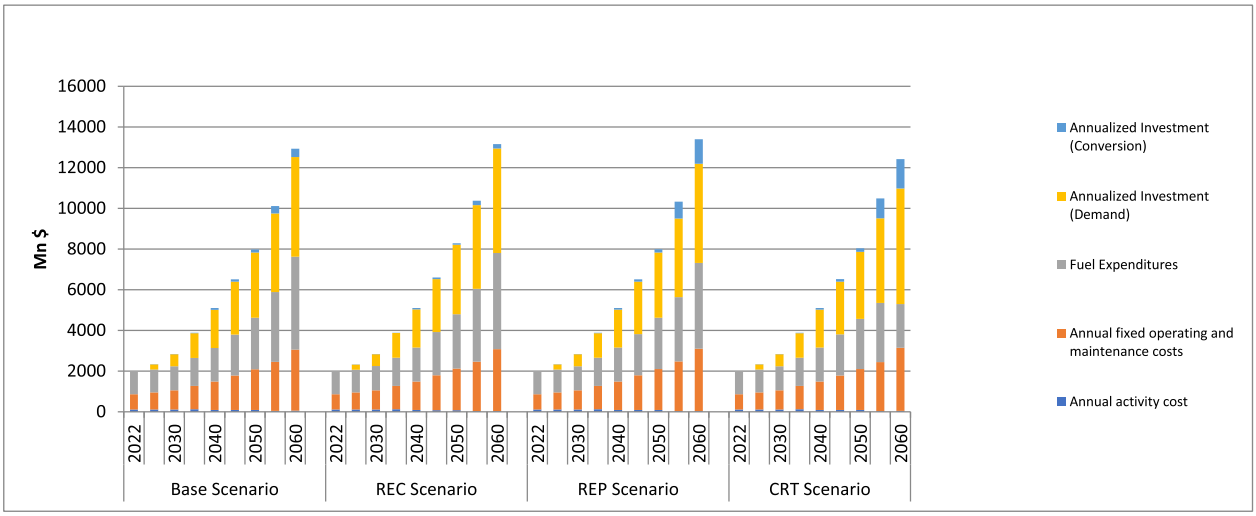

Fig. 16. Annual expenditures (Mn$)- Four Scenarios

in Electricity Consumption (REC), Renewable Electricity Portfolio (REP), and Carbon Reduction Target (CRT) scenarios highlight the effectiveness of the alternative strategies modeled in mitigating the city's carbon footprint.

The analysis further identifies charcoal and diesel as the primary contributors to carbon emissions across all scenarios. This aligns with existing literature highlighting the environmental challenges associated with the reliance on traditional biomass, mainly charcoal, in developing countries (Jiang et al., 2024; Tazebew et al., 2023). Additionally, the significant contribution of diesel emissions underscores the urgent need to decarbonize the transportation sector, an essential source of global greenhouse gas emissions and air pollution, as Shahzad & Cheema (2024) suggested.

To achieve a sustainable future, Kampala must prioritize efforts to reduce its dependence on charcoal and diesel. The study underscores the potential of green mobility solutions, such as the electrified mass rapid transit system proposed in the CRT scenario, to reduce transportation sector emissions significantly. Additionally, promoting the adoption of cleaner cooking fuels and technologies, such as LPG and improved cookstoves, can dramatically reduce household emissions associated with biomass use.

The model demonstrates that a substantial reduction in emissions can be achieved when the commuter buses of the envisioned mass rapid transit system are powered by an extended electrical grid reaching the city's outskirts. This finding strongly supports the strategic expansion of the electricity grid as a crucial element of the sustainable urban transportation plan for the Kampala metropolis. It aligns with research highlighting the potential of electrified public transportation systems to reduce greenhouse gas emissions and improve urban air quality significantly (Palit et al., 2022; Pietrzak, K., & Pietrzak, O. 2020). Furthermore, integrating electric buses into the Mass Rapid Transit (MRT) systems is consistent with global trends toward decarbonizing the transportation sector, as evidenced by the increasing adoption of electric buses in major cities worldwide (Miraftabzadeh et al., 2024).

By extending the electrical grid and electrifying the bus fleet, Kampala can reduce its carbon footprint and improve the reliability and efficiency of its public transportation system. This strategic approach would contribute to a more sustainable and livable urban environment, promoting cleaner air, reduced traffic congestion, and improved accessibility for all residents.

Furthermore, the analysis suggests electrifying freight transportation using electric locomotives. This strategy and electrifying the mass rapid transit system offer a compelling path to reducing reliance on diesel and achieving greener mobility in Kampala. Adopting the Carbon Reduction Target (CRT) scenario presents the most promising path forward based on the KAMPALA-TIMES model's findings. This scenario prioritizes substantial reductions in carbon emissions by focusing on curbing the use of charcoal and diesel. The electrification of the mass rapid transit system and freight transportation, coupled with the expansion of the electricity grid, emerges as a critical element of this strategy. By implementing these measures, Kampala can achieve a sustainable transportation future, balancing economic growth and mobility needs with environmental responsibility.

Overall, the KAMPALA-TIMES model analysis provides a robust framework for understanding the dynamics of carbon emissions by fuel type in Kampala and identifying critical areas for targeted mitigation efforts. The findings emphasize the need for a comprehensive and integrated approach to energy policy that promotes sustainable energy practices, technological advancements, and behavioral changes to achieve substantial carbon abatement and ensure a sustainable future for the metropolis.

4.8. Annual system expenditures

The KAMPALA-TIMES model analysis provides valuable insights into the economic considerations of achieving a sustainable transportation future in Kampala. The findings reveal that while fuel expenditures and annualized investment costs consistently dominate energy system expenditures across all scenarios (Figs. 16 & 17), a crucial trend emerges. These expenditures demonstrably decrease as the model progresses toward the Carbon Reduction Target (CRT) scenario.

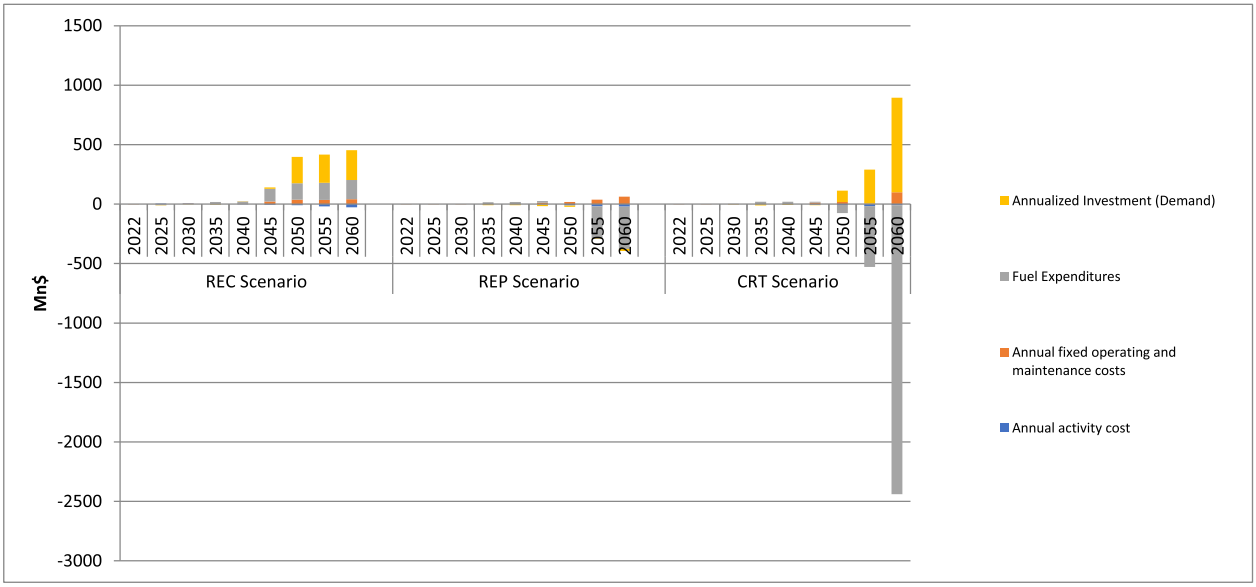

Fig. 17. Annual expenditures- Difference from the BAU Scenario (Mn$)

This observation suggests a compelling trade-off. Although annual fixed operating and maintenance costs are projected to increase, these are more than offset by the substantial reductions in fuel expenditures within the transportation sector over the planning horizon. This trade-off becomes increasingly favorable as the model moves towards the CRT scenario, underscoring the long-term economic viability of sustainable practices.

The study's findings align with the broader literature on the economics of sustainable transportation. Research has consistently shown that while upfront investments in cleaner technologies and infrastructure may be necessary, the long-term savings associated with reduced fuel consumption and improved energy efficiency can outweigh these initial costs (Mushafiq et al., 2023; Jayachandran et al., 2022). Moreover, the economic benefits extend beyond direct cost savings, including improved public health outcomes, reduced environmental degradation, and enhanced overall quality of life.

Based on the model's analysis, adopting the CRT scenario presents the most promising pathway for Kampala. This scenario prioritizes long-term economic sustainability alongside environmental responsibility, demonstrating that a strategic shift in financial priorities can yield significant benefits. By strategically managing upfront investments focusing on fuel efficiency and adopting cleaner technologies throughout the transportation sector, Kampala can achieve greener mobility in the future while minimizing long-term economic burdens (Ismail et al., 2023).

This study employs the KAMPALA-TIMES model, an E3 (Energy-Economy-Environment) optimizing tool, to comprehensively analyze Kampala's transportation sector in the context of achieving green mobility by 2060. The analysis underscores the sector's significant share of final energy consumption and highlights its heavy reliance on fossil fuels for road transportation. This dependence contributes to rising greenhouse gas (GHG) emissions, necessitating a paradigm shift in transportation policy.

The study delves into in-depth transportation analyses, focusing on the potential of cleaner energy sources, reduced energy consumption, efficiency of system technologies, optimization of trip modes, and GHG emission reductions through modal shifts. Recognizing that energy demand and GHG emissions vary across different transportation modes, the KAMPALA-TIMES model explored four scenarios leading toward green mobility by 2060.

The compelling results from this bottom-up modeling approach advocate for establishing a mass rapid transit system anchored by commuter buses and an electrified metro. This integrated system has the potential to significantly alter passenger travel habits in Kampala, paving the way for a more sustainable transportation future by 2060. The model's findings align with a growing body of research highlighting mass transit systems' critical role in reducing emissions and promoting sustainable urban mobility (Winkler et al., 2023; Mavlutova et al., 2023).

Kampala can achieve its green mobility goals by promoting a shift towards cleaner energy sources, reduced energy consumption, and a strategic modal shift anchored by an electrified metro system (Ahmad et al., 2024). This holistic approach will not only contribute to significant carbon reduction but also foster economic growth and address the increasing mobility needs of the city's population (Elavarasan et al., 2022). The findings from this study offer valuable insights for policymakers and urban planners as they navigate the complex challenges of sustainable transportation planning and strive to create a greener and more resilient future for Kampala (Galuszka et al., 2021).

5. Conclusions

This study leverages the KAMPALA-TIMES model to comprehensively evaluate the potential for integrating an electrified metro system into Kampala's transportation sector. Analyzing current transportation patterns, developing four future scenarios, considering energy and environmental impacts, and exploring policy implications highlight the limitations of a business-as-usual approach and the transformative potential of alternative sustainable pathways. The findings underscore the importance of prioritizing energy efficiency, optimizing modal shifts, expanding renewable energy integration, and actively reducing carbon emissions to achieve a more sustainable transportation future for Kampala (Hou. X et al., 2023).

Among the scenarios analyzed, the Carbon Reduction Target (CRT) scenario emerges as the most effective pathway for advancing sustainable urban mobility. This scenario emphasizes the development of mass rapid transit (MRT), anchored by an electrified metro system, to serve as the backbone of Kampala's transportation network (Kuru & Ansell, 2020). The CRT scenario offers a multi-dimensional approach to sustainability by achieving significant reductions in carbon emissions (up to 85% below baseline levels), enhancing energy efficiency, and improving public health outcomes through reduced air pollution (Ulpiani et al., 2023; Njenga & Phiri, 2022). Additionally, the widespread adoption of an electrified MRT system, alongside supporting infrastructure, is projected to stimulate economic growth, foster green job creation, and align with global sustainability goals, including the UN's Sustainable Development Goals (SDGs 7, 11, &, 13) and the Paris Agreement (De Neve & Sachs, 2020; Mutambisi & Chirisa, 2023).

The KAMPALA-TIMES model provides detailed projections on primary energy supply, electricity generation by fuel type, sectoral energy demand, transportation demand by trip mode, carbon emissions, and annual system expenditures. The comparative analysis between scenarios demonstrates the CRT scenario's clear advantage in terms of energy sustainability, economic viability, and environmental responsibility (Venturini et al., 2019). The findings highlight the need for a strategic shift towards cleaner energy sources, reduced dependency on fossil fuels, and investment in an electrified metro system, underscoring the practical implications for policymakers and urban planners (Sekasi & Martens, 2021).

Furthermore, the analysis reveals that transitioning to an electrified metro system can enhance energy resilience and promote a resource-efficient infrastructure that supports Kampala's long-term mobility needs (Virtanen et al., 2020). These insights offer valuable guidance for policymakers, suggesting that a robust policy framework aligned with the CRT scenario can pave the way for a sustainable, resilient, and equitable transportation system in Kampala.

While this study offers significant insights, it is essential to acknowledge its focus on the energy and environmental dimensions of transportation planning. Further research utilizing a recursive dynamic computed general equilibrium (CGE) modeling approach is recommended for a more holistic understanding of the economic implications of the proposed energy transitions. Such an analysis would enable a comprehensive assessment of the macroeconomic impacts associated with the proposed policies and infrastructure investments, providing policymakers with an integrative view necessary for informed, data-driven decision-making.

5.1. Policy implications

This study, informed by the KAMPALA-TIMES model findings, explores the critical role of mass rapid transit with an electrified metro system at its core in achieving sustainable urban transportation for Kampala. Here are five key policy takeaways for policymakers and urban planners:

1. Shift from Business as Usual (BAU): The BAU scenario highlights the urgency of moving beyond current practices. Continued reliance on fossil fuels and a lack of strategic planning hinder progress towards sustainability goals. The CRT scenario promises a sustainable multimodal transportation strategy for the metropolis.
2. Energy Efficiency is Paramount: Scenarios focusing solely on energy consumption reduction (REC) or renewable energy expansion (REP) demonstrate the need for a comprehensive approach. Energy efficiency improvements across all transportation modes, as shown in the CRT scenario, are essential for maximizing the impact of any sustainability strategy.
3. A significant injection of low-carbon electricity is essential. The Carbon Reduction Target (CRT) scenario, emphasizing low-carbon development and mass rapid transit with an electrified metro system at its core, offers the most significant emissions reductions and efficiency gains. Policy frameworks should prioritize electrifying public transportation and promoting hybrid sedans for sustainability.
4. Kampala to hinge firmly on renewable supply energy: The CRT scenario's success hinges on a robust renewable energy portfolio. Investments in solar, biofuels, and hydropower infrastructure are crucial to powering the electrified transportation system and ensuring long-term sustainability.
5. Aligning with Global Goals is within reach: The CRT scenario fosters the achievement of the Paris Accord and SDGs related to clean energy-7, sustainable cities-11, and climate action-13. This scenario allows Kampala to demonstrate leadership in multimodal sustainable transportation practices.

These takeaways underscore the critical role of strategic policy interventions in achieving Kampala's greener and more sustainable transportation future. Policymakers can leverage the KAMPALA-TIMES model findings to guide the city toward a cleaner, healthier, and more livable place by prioritizing low-carbon electrification, energy efficiency, and renewable energy integration.

Declaration of competing interest

I am writing to affirm that there are no conflicts of interest regarding the manuscript 'Sustainable Urban Transportation Planning: Integrating an Electrified Metro System into Kampala Metropolis' Transport Sector,' which I have submitted for publication. I am pleased to note that the topic aligns closely with the scope of the Multimodal Transportation Journal, making it a valuable addition to your publication. As the lead author of this manuscript, I want to emphasize our unwavering commitment to research integrity and impartiality. Neither I nor any of my co-authors have any financial, professional, or personal interests that could be perceived as influencing the research or its findings. Our research has been conducted with the utmost integrity and impartiality, and we have no affiliations or involvements that could give rise to conflicts of interest. We are fully committed to upholding the highest standards of transparency and ethical conduct in our research endeavors. We will provide further clarification or documentation if any questions arise regarding potential conflicts of interest. We sincerely appreciate the opportunity to contribute to the scholarly discourse in the Multimodal Transportation Journal and eagerly await the possibility of our manuscript being considered for publication.

CRediT authorship contribution statement

Ismail Kimuli: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **John Baptist Kirabira:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ismael Nkambwe:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization. **Saadat L.K. Nakyejwe:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Michael Lubwama:** Writing – review & editing, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kasimu Sendawula:** Supervision, Project administration, Investigation, Funding acquisition. **Nashua K Nabaggala:** Writing – review & editing, Supervision, Project administration, Investigation, Data curation.

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