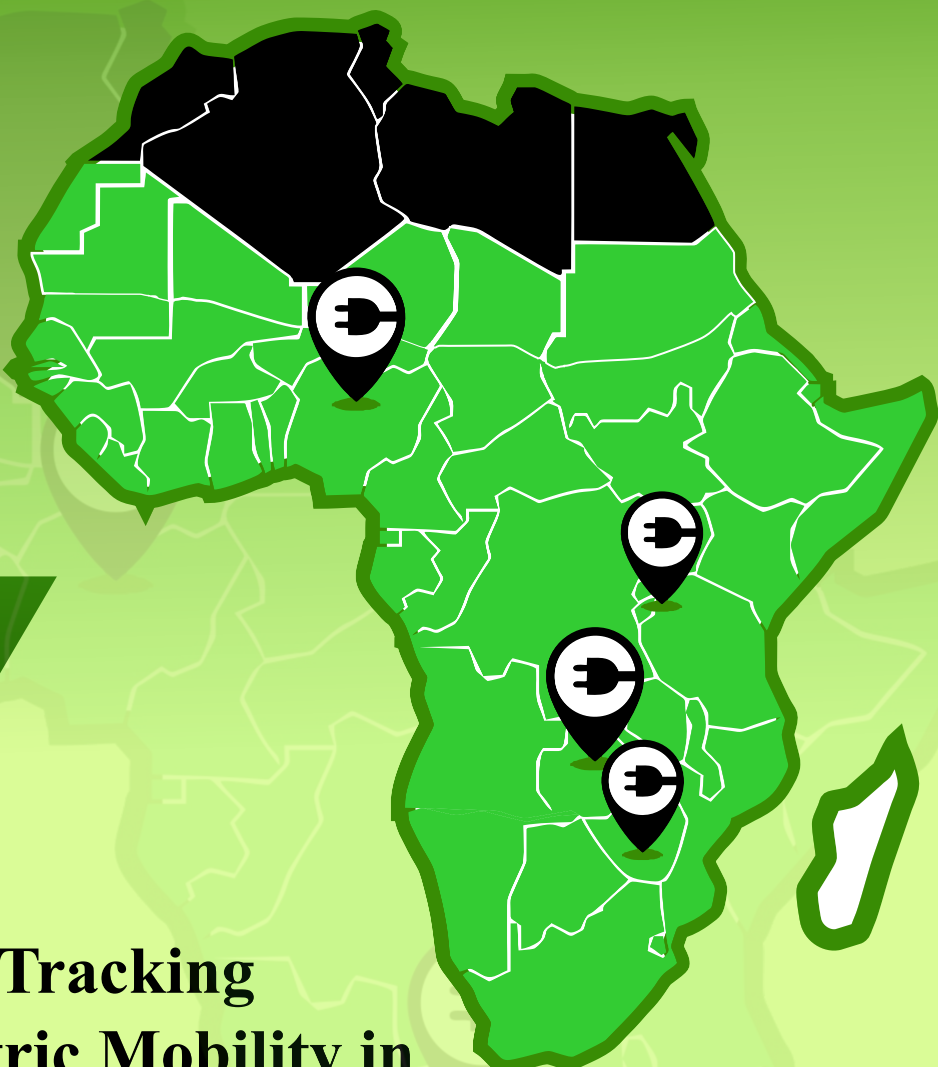
Zambian Electric Mobility Innovation Alliance (ZEMIA)



Fast Tracking Electric Mobility in Sub-Saharan Africa

Fast Tracking Electric Mobility in Sub-Saharan Africa: An analysis of vehicle segment prioritization, barriers to adoption, and policy roadmap development on GHG emissions.

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Abstract

Fast tracking electric mobility in sub-Saharan Africa is a crucial element to overcoming the challenge of anthropogenic climate change. Addressing this challenge requires urgent attention from governments and other stakeholders worldwide in the quest to transform road transport from dependence on Internal Combustion Engines (ICE) to Electric Vehicles (EVs). Given that road transport is responsible for a fifth of all global carbon dioxide (CO_2) emissions, battery electric vehicles (EVs) are being promoted to replace the high emission conventional automobiles. However, the adoption rate of EVs remains low because most countries globally lack the infrastructure and regulatory framework to support their adoption.

This study aims to identify the factors that influence BEV adoption in Sub-Saharan Africa (SSA). Using both a multi-criteria qualitative assessment, and model based quantitative analysis, the study examines factors such as total cost of ownership, battery range and life, charging networks, regulatory environment, and value chain possibilities. Study findings show that EVs are comparatively more expensive than ICE, resulting in their low adoption rate. However, their adoption can help decarbonize the power and transportation sectors. Further, online survey respondents' concerns regarding EV adoption included inadequate public infrastructure, and car attributes such as charge range and battery life.

The paper recommends prioritization of policy measures that address the concerns of the respondents and facilitate adoption enhancers to fast-track electric mobility in SSA.

Keywords: EV, GHG, SSA, Barriers, Prioritization, Vehicle Segments, Policy, Adoption Enhancers, Battery Range, Total Cost of Ownership, Payback, Charging Networks.

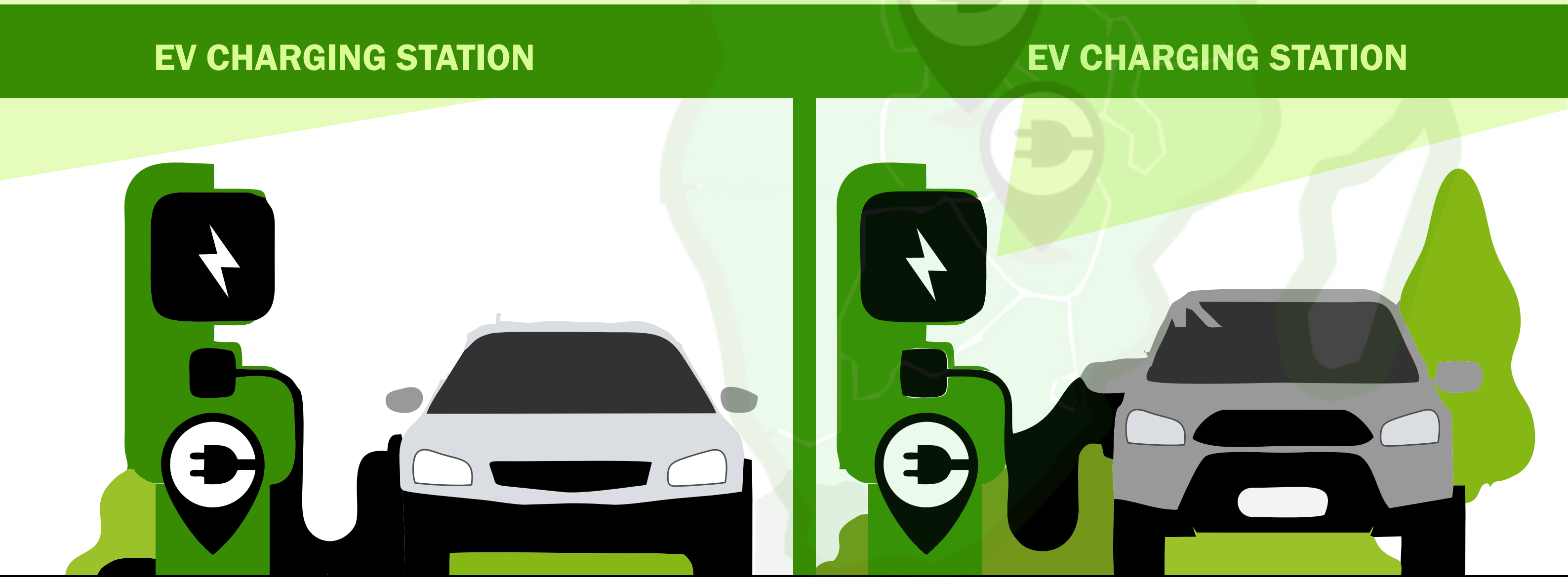
Introduction

1.1. Background & Context

Fast tracking electric mobility is key to addressing the challenge of anthropogenic climate change in sub-Saharan Africa, and globally. Globally, transportation is responsible for a fifth of all carbon dioxide (CO_2) emissions due to combustion of fossil fuels [1, 2]. The transition from Internal Combustion Engines (ICE) to Electric Vehicles (EVs) is borne out of the need to reduce the amount of carbon emissions in the transport sector. In this regard, EVs are widely considered a powerful mitigation option to reduce CO_2 emissions from various vehicle segments including passenger cars, and two and three-wheelers in the transport sector [3]. With the Paris agreement on climate change commitment to limit global warming to 1.5 ◦C, climate science shows that the world overall has to hit net-zero CO_2 emissions by 2050 if the 1.5 ◦C goal has to be achieved [2].

To reach the Net Zero Scenario, emissions from the transport sector must be reduced by 20%, to less than 6 gigatons by 2030 [4]. Achieving this reduction will require the rapid electrification of road vehicles, improvements in operational and technical energy efficiency, the promotion and commercialization of low-carbon fuels in the maritime and aviation sub-sectors, and policies that encourage a shift to less carbon-intensive travel options such as non-motorized transport [5]. Although mobility is essential for social and economic progress, the transportation industry in many countries currently remains one of the main polluters of the environment, signaling the imperative need to transition from ICE to EVs [4, 5].

The International Energy Agency (IEA) indicates that for a Net Zero CO_2 emissions transition globally by 2050, 60% of the global car fleet should be electric by 2030 [1, 4]. In addition, predictions suggest that the global electric vehicle (EV) sector is expected to expand at a compound annual growth rate (CAGR) of 15.9% between 2023 and 2035, with 2050 predictions indicating that 80% of all new vehicles sold worldwide will be electric [4, 5] . Compared to ICE vehicles, EVs have approximately 65 to 85 percent lower life-cycle emissions in Europe, and they also contribute to an improved quality of life in urban areas by reducing air and noise pollution [6].



Introduction - Cont.

The Global Electric Mobility Readiness Index (GEMRIX) compares the market circumstances for ICE vehicles and EVs. This index considers the benefits of buying and operating an EV compared to those of an ICE vehicle in a nation that scores 100 on the EV readiness scale. The 2022 GEMRIX indicates that most countries in the world do not currently have the right conditions for BEV uptake [7]. Norway is currently considered the sole market worldwide that is fully prepared for EV adoption and has a score of 115 on the 2022 GEMRIX [7]. China, Germany, the UK, and Singapore are ambitious followers, with scores of approximately 80 [7].

Emerging EV markets include US, Japan, UAE, and Thailand with scores ranging between 40 and 60 [7]. The least ranking group on the GEMRIX includes a cohort of starter countries including Mexico, India, Brazil, Indonesia, Vietnam, and South Africa [7]. It must be noted however that there are limitations to using the GEMRIX because it only considers four-wheeled vehicles. This restricted definition of EVs excludes two- and three-wheeled vehicles which make up the majority of EVs available on the global market Figure .Global Electric Mobility Readiness Index — GEMRIX 2022[4][5, 8].

1.1.1. E-Mobility in Africa

Power crises experienced in various African countries in recent years have necessitated significant investments in the power sector to enhance energy availability, promote environmental sustainability and upscale e-mobility [9]. With the continent projected to experience high population growth, urbanization, and an increase in motorcycles and motor vehicles, there is also expected to be a significant rise in vehicle ownership [10]. As the global EV movement gains momentum, African nations have the opportunity to pursue a sustainable and cost-effective energy path, while avoiding to commit to energy infrastructures and vehicles that are high in carbon emissions [9, 11].

In many countries, particularly those in Sub-Saharan Africa, low-density urban expansion results in reduced access to urban facilities and a surge in motorization, making the provision of sustainable mobility a challenging issue [11, 12]. Insufficient transportation in Sub-Saharan Africa continues to impede the access of more than 70% of the rural population to jobs, education, and healthcare services, equating to an estimated 450 million people [12]. While more than 128 million Africans, representing over 10% of the total population of the continent, currently reside in large cities, this number is expected to double by 2050 [10].

Africa's rapid population growth is likely to coincide with low-density urbanization. The resultant effect is a threefold increase in the urban footprint of cities in less developed countries [13]-[17]. This urban sprawl often means limited accessibility for disadvantaged communities and encourages affluent individuals to purchase polluting private vehicles. Despite being low, the use of passenger and commercial vehicles is increasing in African nations. In Kenya, a more economically advanced country in East Africa, the fleet of vehicles is expanding at a rate of 12% per year, with 80% being used cars [18].

Introduction - Cont.

With the exception of four African countries, namely; Egypt, Morocco, South Africa, and Sudan, majority African countries have relaxed import age restrictions for vehicles resulting in majority of imports being old model used vehicles [17]. As a result, the rise in motorization is accompanied by a decline in fuel efficiency across much of the continent [17, 18]. However, there is an opportunity for Sub-Saharan Africa to introduce eco-friendly mobility technology and policies, to curb polluting motorization trends, improve safety and enhance accessibility.

While the road transportation sector accounts for 14% of global greenhouse gas emissions, land transport emissions in Africa are among the fastest growing worldwide [19]. Fuel consumption from road transportation in Africa increased by 82% between 2000 and 2012, resulting in an 88% increase in emissions from 49 million tonnes of carbon dioxide equivalent (tCO_2 eq) to 92 million tCO2 eq [19-21].The emissions from ICE vehicle exhausts, which include substances like particulate matter, nitrogen oxides, and carbon monoxide, are a primary contributor to respiratory and cardiovascular illnesses in urban regions, especially among impoverished communities and children [22-25]. To effectively tackle these concerns that are both environmental and social in nature, it is essential to enhance the mobility and access to services for most people.

Improvements to privately-owned mini-buses, buses, motorcycle taxis, and tuk-tuks, collectively known as 'popular transit' or 'paratransit,' are necessary to improve road transportation in Sub-Saharan African cities. In these cities, paratransit makes up a significant portion, accounting for 70 to 100% of public transport services, and up to 50% of travel modes [26]. Although paratransit is accessible to many residents, the most vulnerable citizens cannot afford the fare [27-28]. For instance, low-income residents in Kampala spend 25% of their family income on transportation [15, 24]. Consequently, most low-income commuters, especially women, are compelled to walk due to their financial constraints [25]. A study conducted by the University of California on 4,375 slum dwellers in Nairobi revealed that 53% of low-income men and 67% of low-income women walk to work, in contrast to 36% of working men and 47% of working women who are not poor [25].

To attain sustainable transportation, e-mobility is essential, and the use of EVs is becoming more prevalent globally [1, 5]. E-mobility is defined by the researchers in this study as the movement of people and goods facilitated by electric vehicles that utilize batteries to power their engines. The batteries are charged using electricity from external sources. On a global scale, EVs have the potential to decrease greenhouse gas emissions, mitigate climate change, enhance accessibility, improve public health, and boost economic growth [3]. For instance, the collective use of all types of EVs in 2019 helped prevent 53 Mt CO_2-eq of emissions (i.e., avoiding 0.6 million barrels of oil products daily) [27].

Evs also decrease local pollutants that have harmful health impacts. In South Africa, transportation was responsible for 7% of pollution-related morbidity in 2015, translating to roughly 1,400 deaths and $1.5 billion in health-related costs [28]. A study by the International Council on Clean Transport (ICCT) evaluated urban fleets in 20 cities, including 7 in Sub-Saharan Africa, and found that battery electric buses produce fewer greenhouse gases (GHG) than diesel buses over their lifetime, particularly in cities that use renewable energy sources [29, 30].

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Poorly built and outdated vehicles often cause traffic accidents resulting in fatalities of motor vehicle occupants, pedestrians, and bicyclists [29]. New EVs are built to meet higher safety standards, which can save lives and generate revenue [30]. Research further suggests that cutting traffic fatalities in half can increase GDP per capita by 7 to 22% [29, 30]. In Uganda, road accidents and fatalities cost up to USD 1 billion in 2015, which amounted to 0.16% of its GDP [23].

While electric mobility, or e-mobility, is an essential component of achieving sustainable mobility, it is not sufficient on its own. The integration of e-mobility with better urban and transportation planning is crucial to ensuring accessibility for all and efficient operations [30]. This primarily entails moving away from car-centric planning towards increasing usage of public transit and non-motorized transportation such as walking and biking [31- 33]. An international study conducted in 2015 projects that doubling the number of bicycle and electric bicycle riders globally by 2030 would reduce urban transport energy consumption and CO_2 emissions by approximately 7% [32].

Vehicle fleets vary considerably throughout Africa. In a large number of countries ranging from Mozambique to Senegal, the use of two- and three-wheeled vehicles is on the rise and accounts for a significant portion of fleets, making up around 60-70% of all vehicles in Tanzania, Uganda, and Togo [33]. However, in much of Southern Africa and a few other countries like Gabon, they have not become popular, with four-wheeled personal vehicles and minibuses dominating the road transport [33]. The ability of these different vehicle fleets to transition to electric power is substantially different, primarily due to the higher cost of batteries, which are larger and more expensive in larger vehicles [34].

Due to the dominance of two- and three-wheeled vehicles in many African countries, e-mobility startups in Sub-Saharan Africa have primarily focused on this smaller vehicle segment [33]. At least 45 companies have been identified as working to introduce electric scooters and motorcycles in the region, while only 10 companies solely focused on four-wheeled passenger cars [33]. Startups such as Spiro (formerly M-Auto), Ampersand, and Zembo have established battery-swapping stations and deployed hundreds or thousands of electric scooters and motorcycles in countries such as Togo, Rwanda, and Uganda [33]. However, these startups still face significant challenges, including high upfront costs and a lack of charging infrastructure [30, 33].

There are still major challenges to the widespread adoption of EVs worldwide. For instance, it is expected that Latin America will need over 6,600 public slow charging stations and 3,300 public fast charging stations by 2025, which will cost a total of $757 million in infrastructure investment [32]. Moreover, countries with limited electricity access and highly carbon-intensive energy systems will face more difficulties in adopting net-zero emissions EVs [32]. The transition to e-mobility is a process that takes time due to its potential impacts. It typically occurs gradually with the introduction of new vehicles and infrastructure supported by the development of legislative frameworks and asset financing [30].

1.1.2. Electric Vehicle Types

Sustainable passenger transportation includes both motorized and non-motorized modes such as walking, biking, buses, trains, private cars, scooters, and motorcycles. Electric mobility solutions have been adopted in various modes of transportation worldwide, ranging from large to small. EVs are classified into four types, based on differences in powertrain and propulsion systems: hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), 100% electric or battery electric vehicles (BEV), and fuel cell electric vehicles (FCEV). Below we describe the different forms of motorized and non-motorized modes of transportation.

1.1.3. Bicycles, Motorcycles, and Rickshaws (Two- and Three Wheelers)

The popularity of two- and three-wheeled vehicles can be attributed to their maneuverability in busy urban areas, ability to serve as a convenient first/last-mile connectivity option, and affordability for low-income consumers [33]. These vehicles have gained traction in developing and low-income countries such as regions in Asia, Latin America and the Caribbean, and Sub-Saharan Africa, where rapid urbanization has led to increased traffic congestion [32]. Additionally, two- and three-wheelers are often used as productive assets, such as motorcycle taxis [35]. In some areas, electric motorcycles and rickshaws are becoming cost-competitive with their petrol-based counterparts, which is a crucial factor contributing to their adoption [32]. While electric two- and three-wheelers typically have higher upfront costs than petrol-based vehicles, they offer lower Total Cost of Ownership (TCOE) due to lower maintenance and energy costs [30]. Plug-in technology is incorporated in two and three-wheelers, which enables them to be charged at home or through battery-swapping programs where companies exchange used batteries for fully charged ones [33]. Moreover, these vehicles are often used for transporting goods, which became more prevalent during the COVID-19 pandemic when many city administrations-imposed restrictions on the movement of people to curb the spread of the disease. [35- 38].

1.1.2.2. Buses and Minibuses

An increasing number of manufacturers, such as Proterra and BYD, are concentrating on producing EVs that are specially created for buses [34]. These EVs utilize overnight charging depots, which can be complemented by overhead and quick charging stations installed at crucial points along the vehicle's route. China currently operates over 98% of the world's e-bus fleet, approximately 500,000 buses. In 2017, Shenzhen in China was the first city globally to electrify all of its 16,000 buses [34, 37].

From 2019 to 2022, the number of e-buses in Europe, North America, South America, and India has surpassed previous records [39]. Santiago, the capital city of Chile, now has the largest e-bus fleet outside of China with over 400 buses [35]. However, coordinating the electrification of public transportation is challenging in areas where services are dispersed and privatized, such as Cairo in Egypt and Addis Ababa in Ethiopia [36]. In Kenya, BasiGo has been rolling out BYD buses for the matatu paratransit service, using a financial model which splits battery and vehicle costs [25]. While no results have been disclosed at the time of this research, some recent pilot studies are assessing the feasibility of electrifying fragmented public transport service providers in Sub-Saharan African cities.

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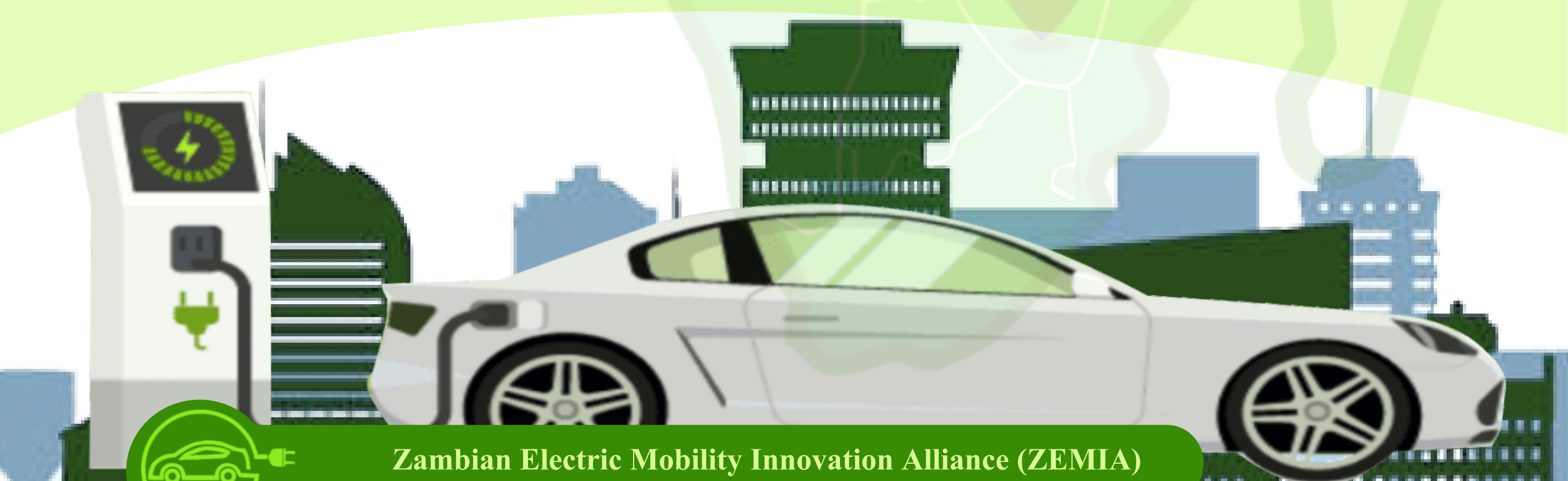
1.1.2.3. Trains, Light Rail Trains (LRTs), Metros, and Cable Cars

The train is the earliest form of electrified transportation, using electricity supplied through overhead cables or tracks to power a motor [38]. Trains were first built with steam engines that ran on coal, but they were electrified in the 1890s and are now widely used worldwide, especially for narrow gauge and light rail transportation in cities such as Addis Ababa, Cairo, Nairobi, and Kampala. Trains are used for both freight and passenger transportation [38].

1.1.2.4. Private Cars

Due to their usage in high-income countries, electric passenger cars have been often used as the face of the e-mobility transition, produced by established companies such as Tesla, BMW, BYD, Nissan, and Toyota Prius, among others. Bloomberg NEF (BNEF) predicts that by 2040, 31% of all passenger vehicles in use will be electric, accounting for over half of all global passenger vehicle sales [39]. According to a 2018 BNEF projection, the ownership costs of EVs will soon be equivalent to those of gasoline vehicles, including lifetime maintenance, fuel, and battery expenses [39 - 41].



1.1. Problem statement & Rationale

There is no definitive solution to the question of how EVs will affect the energy system because the effects of EVs vary greatly depending on various elements, such as the mix of power generation, usage patterns, and behavior. Few studies have specifically addressed Sub-Saharan African nations and the unique characteristics of EV development in these nations.

1.2. Aims and Objectives

This article aims to explore ways to fast-track the adoption of electric mobility in Sub-Saharan Africa (SSA) with a focus on Zambia, Zimbabwe, Rwanda, and Nigeria. The study intends to develop an electric mobility policy framework and market readiness plan that promotes modern, sustainable, and results-driven transportation systems. Additionally, the research aims to deliver a roadmap for the deployment of EVs and charging infrastructure, evaluate the market's viability, and establish a business case for implementation.

To achieve these aims, the study employs a multi-criteria decision-making approach to prioritize vehicle segments in the region based on 23 assessment criteria. The barriers to the prioritized vehicle segment are then comprehensively analyzed using the same approach. The identified barriers are then ranked to determine the most critical factors that need to be addressed to enable electric mobility in SSA, including Zambia, Zimbabwe, Rwanda, Ghana, and other countries. This ranking feeds into a policy roadmap for each country.

Using the policy roadmap, the study also benchmarks the initial cost of adopting electric mobility against traditional petrol/gasoline vehicles, diesel vehicles, and various types of EVs, including EVs, HEVs, PHEVs, and FCEVs. Additionally, the study evaluates the potential greenhouse gas and air pollutant benefits of EVs in comparison to traditional ICE vehicles.

Overall, this research aims to provide a comprehensive understanding of the challenges and opportunities for implementing electric mobility in SSA, along with actionable recommendations for policymakers and industry stakeholders to promote sustainable transportation systems in the region.

The key benefits of this study are the guidelines that could prove useful to government bodies, public and corporate organizations that deal with e-mobility, sustainability or eco-friendly business solutions, as well as automotive manufacturers and suppliers. These guidelines could assist them in creating and presenting solutions to overcome the existing barriers to EV adoption. By removing these obstacles, more customers might be encouraged to opt for EVs.

The following sections are included in this paper: First, we presented the background, motivations, and objectives for this study. Chapter 2 reviews the relevant academic literature and related studies, while Chapter 3 outlines the methodology. The results are presented in Chapter 4, based on the methodology. In Chapter 5, we discuss the findings and provide recommendations to conclude the paper.

2. Literature Review

2.1. Global and regional trends

The market for renewable energy is thriving, particularly in the electric automobile sector [41]. In 2021, global sales of EVs doubled from the previous year, reaching a record high of 6.6 million [4-5, 41-42]. This is a significant increase compared to 2012 when only 120,000 EVs were sold worldwide [41-42]. In 2022, more EVs are sold each week than the 2012 annual number [4, 5]. The growth of the EV market has been impressive, with a fourfold increase between 2019 and 2021, leading to 10% of all vehicles being electrified [39]. Consequently, there are now more than 16.5 million electric vehicles on the roads worldwide, a threefold increase from 2018. The electric vehicle market continues to expand, as evidenced by the 2 million electric vehicle sales in the first quarter of 2022, representing a 75% increase from the same period in 2021 [42].

Thus far, only China has achieved a considerable deployment of electric cars in the heavy-duty industry, primarily because of significant government support [37]. Nevertheless, other countries have announced their intentions to support the electrification of large trucks in 2021 [42-44]. As reported by truck makers, over 170 new models of electric trucks were available outside of China in 2021 [42]. However, swift deployment will be necessary to keep up with official announcements, and more effort will be required to achieve net-zero objectives. Electric trucks represented only 0.3% of all vehicles sold globally in 2021 [42]. In the Announced Pledges Scenario, this figure should reach at least 10% by 2030, and at least 25% in the IEA's Net Zero Emissions (NZE) by 2050 [42]. The market sector that can be electrified most quickly is short-haul vehicles, and the majority of these do not require a large charging network if depot charging is available [45]. Longer-range trucks, however, will require high-power chargers, which are currently expensive and typically require significant grid upgrades [45]. Therefore, early planning and investment are critical to reducing grid strain and establishing a feasible network for the next phase of heavy-duty vehicle electrification.

2.2. Trends in Electric Light-duty Vehicles

Figure 1 shows trends that over 16.5 million electric cars were on the road in 2021, a tripling in just three years.

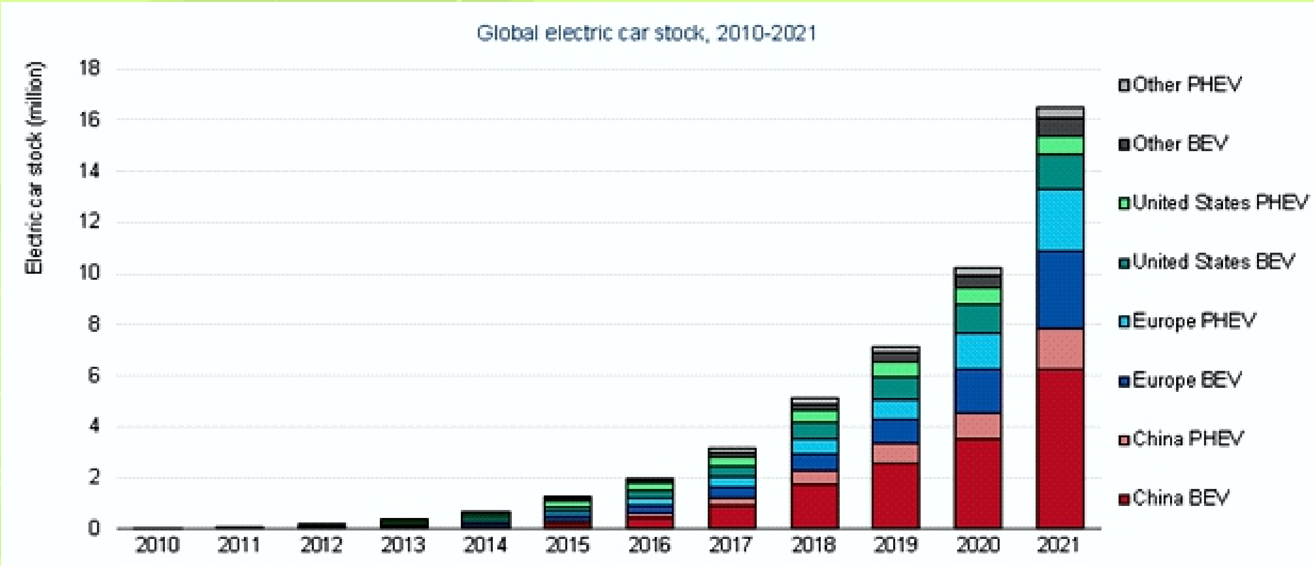
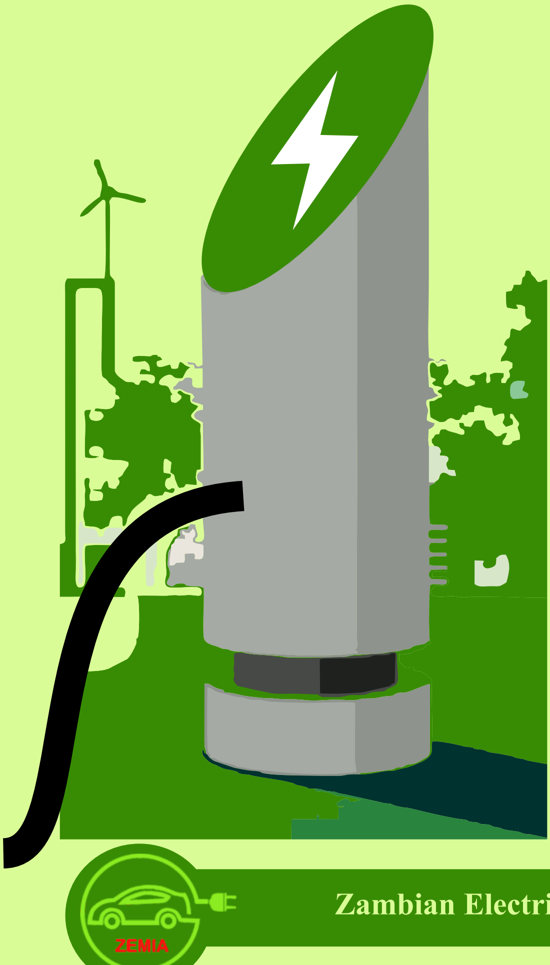


Figure 1. Trends in the electric light vehicle at a global scale [40]



1.1.1. Electric Light-Duty Vehicles

The adoption of EVs in SSA varies from country to country, with some countries such as Kenya and Rwanda showing preference for two and three-wheelers, while others like South Africa, Zimbabwe, and Zambia prioritize light four-wheelers. According to data from the McKinsey Center for Future Mobility [43, 44], electric two-wheelers have the highest probability of being embraced in sub-Saharan Africa. The author considered two scenarios, including the base-case scenario, which primarily reflected the market situation at the time [32]. In the second case study, known as the Accelerated example study, market players actively developed the EV market, and there was low legislative support for the EV transition. Instead, EV availability and affordability drove uptake. According to this prediction, two-wheeler sales would electrify more rapidly in both scenarios and would account for 50–70% of total sales by 2040 [32].

2.2.2. Zero and low-emissions buses

In sub-Saharan Africa, some countries and private companies are considering the use of "cleaner" fossil fuels as an interim solution to reduce carbon emissions from transportation. These fuels include liquefied petroleum gas (LPG), compressed natural gas (CNG), or autogas. Using LPG or CNG can result in a 10-15% reduction in carbon emissions compared to petrol, but this is much less than the 40% (and up to 100%) reduction achieved by electric vehicles (EVs), even in countries where electricity is generated mainly from fossil fuels. Therefore, LPG and CNG are viewed only as transition fuels on the way to achieving zero-emission transport. Hydrogen is another option, and it can have minimal to no carbon emissions if produced using green or blue methods. However, at present, hydrogen production costs make it economically viable only for larger vehicles such as heavy trucks, according to the Hydrogen Council [32].

2.2.3. Types of electric vehicle segments

2.2.3.1. By Number of Wheels

Electric two and three-wheelers

In many low- and middle-income countries, the most rapidly expanding mode of transportation is two and three-wheeled vehicles [44]. Although Asia has the largest number of motorcycles in the world, a few African countries are experiencing significant growth rates [44]. Presently, there are 270 million motorcycles in use worldwide, with 52 million sold each year [44]. This number is expected to rise by 50% to over 400 million motorcycles by 2050 [32].

Research reveals that priority should be given to two- and three-wheelers in the transition to electric mobility [32]. If 90% of motorbike sales globally switch to battery electric by 2030, it could result in an approximate reduction of 11 billion tons of CO_2 emissions between now and 2050, according to the UN Environment eMob calculator's scenario projections [45- 49]. Despite the increased cost of electric motorbikes, it is estimated that the total cost savings from reduced gasoline and maintenance expenses could reach around USD 350 billion by 2050 [32]. UNEP is an organization that advocates for the use of electric two and three-wheelers in Africa, states that this transition will mark the beginning of a shift away from ICE and towards electric and non-motorized two and three-wheelers in sub-Saharan Africa.

Presently, the UN Environment Programme is financing electric two- and three-wheeler initiatives in 16 countries across Asia, Africa, Latin America, and the Caribbean, including Bangladesh (through UNDP), India, Maldives, Nepal, Ethiopia, Morocco, Kenya, Rwanda, Uganda, Burundi, Madagascar, Sierra Leone, Tanzania, Togo, Philippines, Thailand, and Vietnam [29].

2.2.1. By propulsion

Figure 2 illustrates the four primary types of electric vehicles, which include fuel cell electric vehicles (FCEV), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV) with series-parallel and parallel variants. [40].

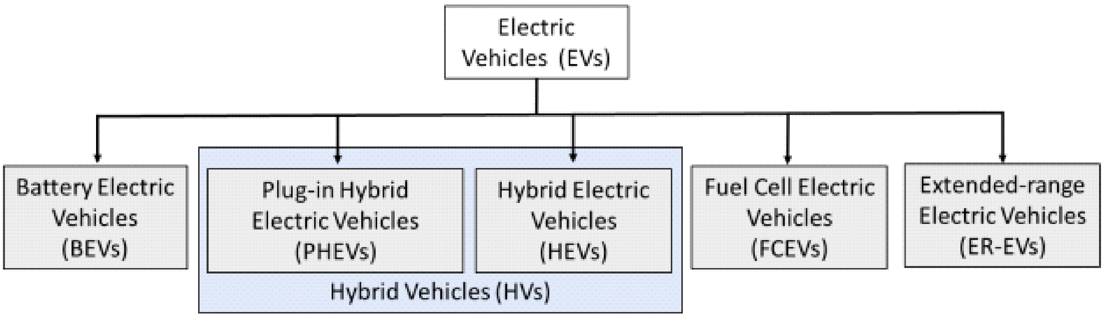


Figure 2. Electric vehicles classification according to their engine technologies and settings

Various hybrid electric vehicles are commonly referred to as "electric vehicles" [43]. An electric vehicle can have one or more energy storage devices, and when it runs on a combustion engine, the wheels are not operated directly by a mechanical transmission. Figure 3 illustrates the fundamental components of an electric vehicle, while Figure 4 shows those of a hybrid electric vehicle. Table 1 lists several of the most popular electric vehicle models currently available.

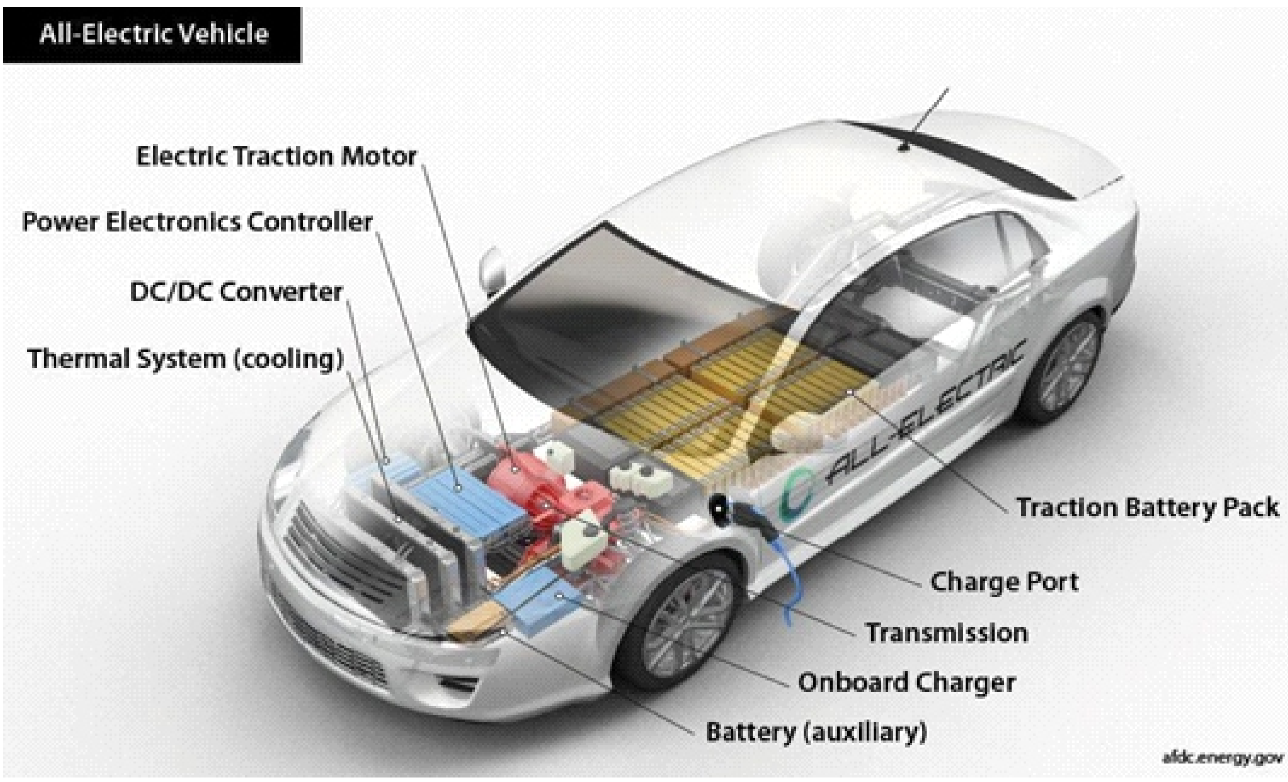


Figure 3: Major parts of an all-electric vehicle [40]

2.2. Trends in Electric Light-duty Vehicles - Cont.

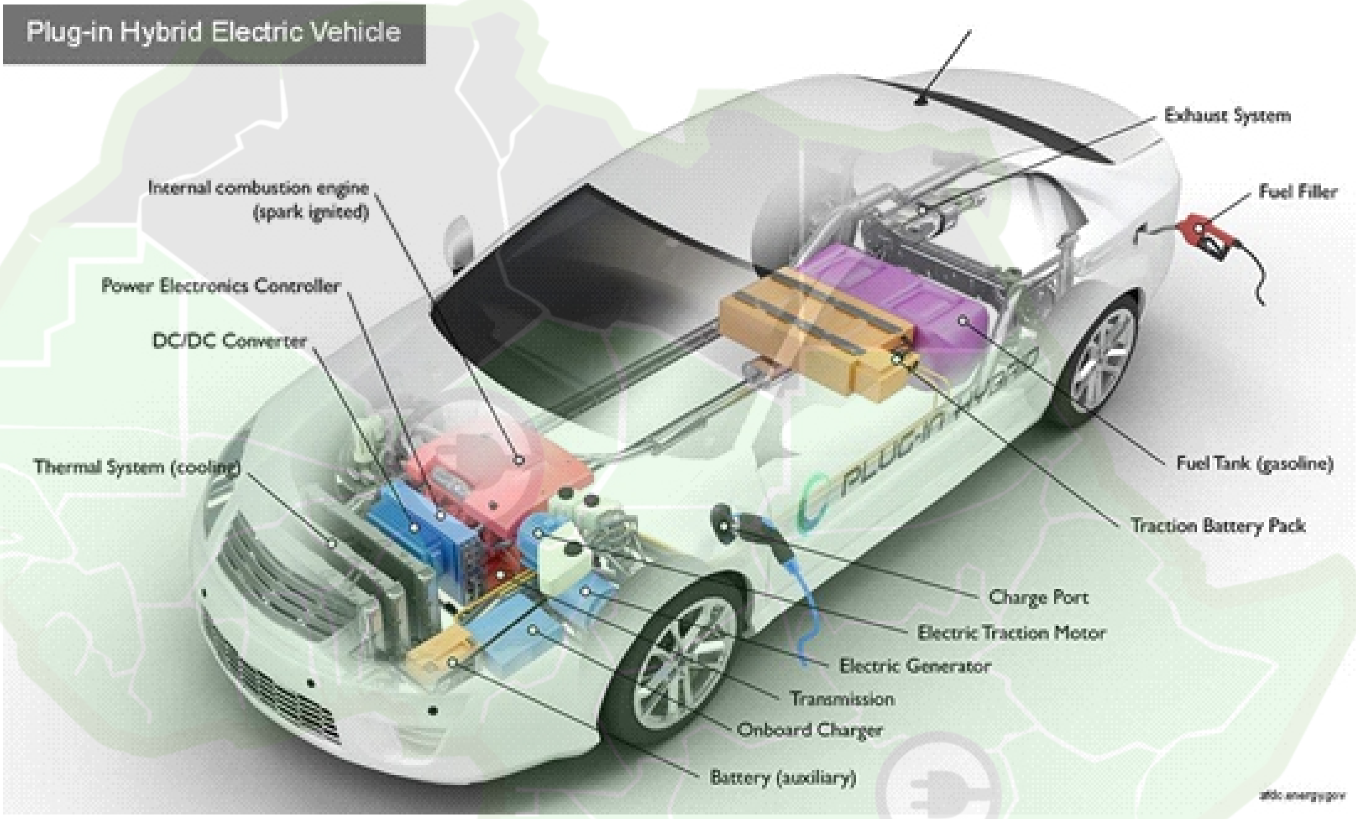
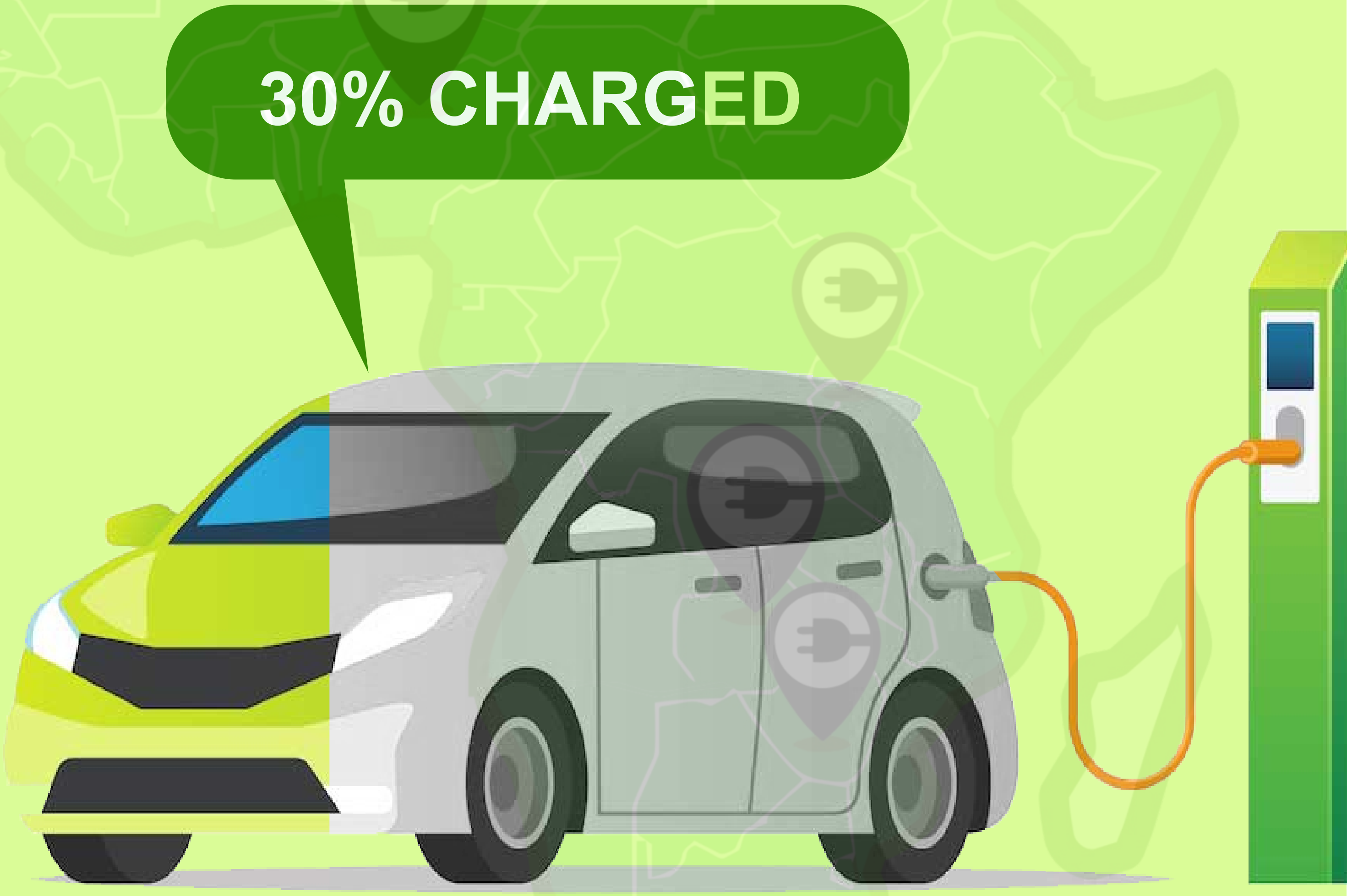


Figure 4: Major parts of a plug-in- hybrid Electric Vehicle [40]

2.3 Policy

In order to participate in the e-mobility industry and reap its benefits, sub-Saharan African governments must implement policy and regulatory measures, such as local content requirements. This is necessary to ensure that Africa plays a significant role in the e-mobility value chains [41]. To achieve this, investments must be made in the automotive industry value chains on the continent to guarantee Africa's continued relevance in the future. There are already efforts being made by sub-Saharan African countries to prepare for this transition, and table 1 illustrates some of the progress that has been made thus far.



2.3 Policy - Cont.

Table 1. E-mobility Sub-Sahara African Policy Framework

No.	Country	Policy achievement
1	Rwanda	A road map for e -mobility transition in Rwanda [42]
2	Zimbabwe	National Electric Mobility Policy and Market Readiness Framework for Zimbabwe [43]
3	Ghana	National Electric Mobility Policy and Market Readiness Framework for Ghana [44]
4	Kenya	The National Energy Efficiency and Conservation Strategy 2020 envisions the country meeting a 5% target of electrified vehicle stock by 2025 [45]. The Finance Act of 2019 has been amended to include the reduction of excise duty for 100% battery -powered electric motor vehicles from 20% to 10% [46]. The National Climate Change Action - There is also an ongoing revision of the Integrated National Transpo rt Policy (2009) to include EVs and related infrastructure. Baseline study on the potential for power-to-x/green Hydrogen in Kenya. An e-mobility tariff is in the process of being implemented; however, it is an

2.4 Sustainable Transport Landscape in SSA

In sub-Saharan Africa, some governments have implemented measures to promote the use of electric vehicles, including tax breaks for EV purchases in Rwanda [45]. Zimbabwe and Ghana have also implemented policies to encourage EV adoption [46-47]. Furthermore, an ecosystem of electric vehicle startups is emerging in the region, with a particular focus on electric two-wheelers [49-51]. According to McKinsey, by the end of 2021, this ecosystem will have included around 20 startups that have raised over $25 million in funding [51].

Sub-Saharan Africa is making progress towards electric transportation; however, there are still several challenges that need to be addressed. These include unstable electrical supply, high vehicle costs, and the prevalence of used vehicles [52]. Despite progress in expanding access to electricity, electricity reliability remains a challenge, with less than half of grid-connected individuals receiving stable electricity according to a 2019 survey of 34 African countries [53]. The SAIDI for sub-Saharan Africa in 2020 was reported at 39.30%, which is significantly higher than the 0.87% reported for OECD high-income countries. Nonetheless, all six of the countries mentioned have urban electricity availability rates above 70%, with some even exceeding 90% [54].

The second issue is affordability, which is influenced by relatively low household incomes, a lack of accessible asset financing, and higher EV sticker prices.

The introduction has highlighted the issue of used cars dominating much of the sub-Saharan African passenger car segment (except for a few countries such as South Africa where used vehicle imports are prohibited). In most of the countries in the region, around 85% of all four-wheel vehicle sales are used cars [32]. This situation is due to problems related to pricing and weak regulation, with many countries allowing imports of vehicles that are over 15 years old and have less strict emissions requirements (reference). According to a 2020 assessment by the United Nations Environment Programme (UNEP), laws regulating used vehicles are either lacking or very weak in 40 of the 49 sub-Saharan African countries [32]. This presents a challenge for new electric vehicles, which will find it hard to compete with the cheap, old internal combustion engine (ICE) cars that are widely available in the region. Furthermore, with 40% of all used vehicles exported globally ending up in Africa, there is a risk that the continent will become a dumping ground for ICE vehicles while the rest of the world transitions to electric transportation [32].

2.5 Barriers to Adoption in SSA

In high-income countries (HICs), electric vehicles (EVs) are typically characterized by certain factors such as high quality, mass production, urban use, government support, and the assumption that the electricity sector can meet demand. However, these characteristics may not be suitable for Sub-Saharan Africa (SSA) due to three main reasons. First, the modes of transportation and types of vehicles in SSA differ from those in HICs. Second, there may be differences in available capital. Third, the electricity networks in SSA may be less reliable compared to those in HICs. Therefore, it may not be appropriate to impose the same approach to vehicle electrification that is used in HICs onto SSA [52].

2.5.1. Financial Barriers

To adopt EVs, financial obstacles such as high purchase costs, battery expenses, knowledge of fuel and maintenance costs, as well as resale value need to be addressed [53]. Compared to ICEVs, EVs offer fewer features due to the absence of economies of scale that characterize new technology development, resulting in customers paying more for EVs [54]. This is why the price of EVs is usually cited as the main obstacle in customer surveys [53]. Battery costs also contribute significantly to the cost of EVs, with size, cost, and range increasing as battery capacity rises [54].

Despite these challenges, EVs offer benefits such as lower fuel and maintenance costs [52]. Electricity serves as the fuel for EVs, which is more affordable and has less direct emissions than gasoline used by ICEVs [55]. Moreover, EV motors are simpler than ICEV motors, leading to lower maintenance costs [53]. However, in addition to technology and utility, consumer purchasing decisions are influenced by other factors.

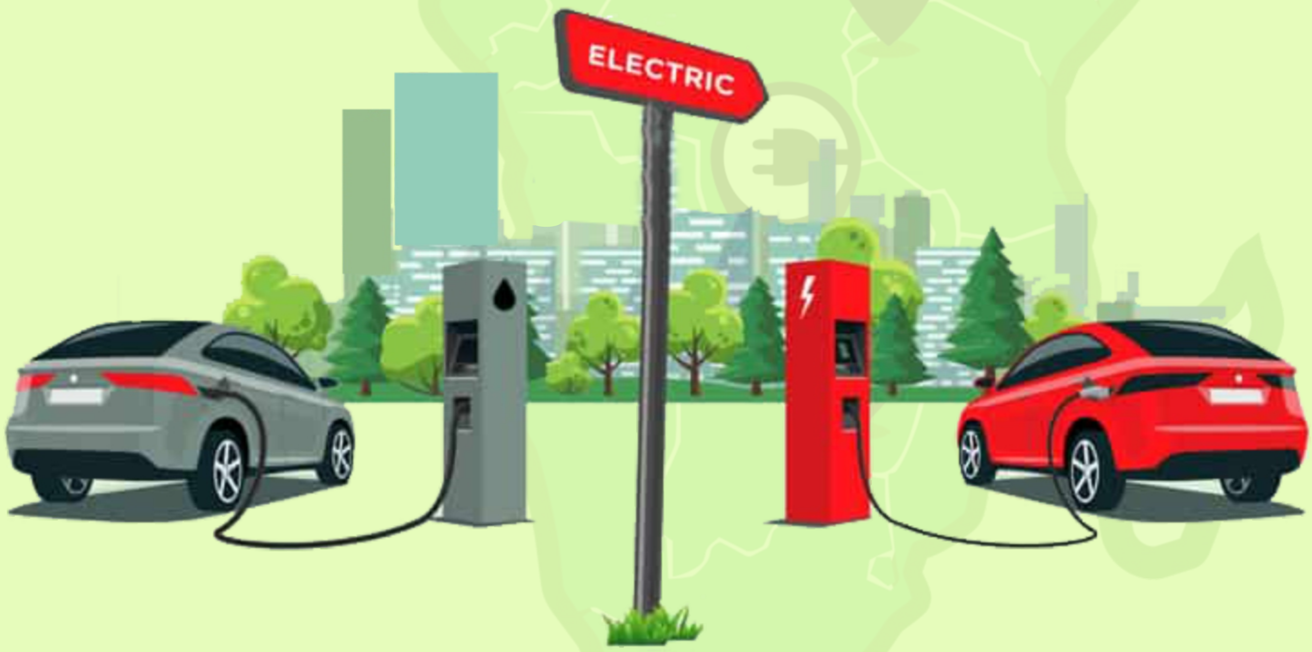
2.5.2. Vehicle Performance Barriers

The performance limitations of EVs may include range, engine power, reliability, battery durability, charging speed, safety, size, and design [56]. Many studies have shown that the major barriers to EV adoption are related to their performance and range [52]. Drivers cannot accurately estimate the distance they can travel or the duration of a trip due to the remaining battery power, resulting in battery depletion during driving [56]. The limited range of EVs causes range anxiety when traveling long distances [57]. Individuals who test drive EVs have also expressed concerns about their reliability, dependability, and safety [58]. Customers are particularly dissatisfied with the limited options for EV sizes and designs available in the market [59].

2.5 Barriers to Adoption in SSA - Cont.

2.5.3. Infrastructure Barriers

The limited range of EVs, similar to the issue of gas stations for ICEVs, is a significant obstacle to their adoption [53]. To promote the widespread use of EVs, it is crucial to have a reliable charging infrastructure, including public charging stations and overnight home charging options [53]. Public charging stations are crucial for increasing the competitiveness and popularity of EVs, while home charging options improve convenience and ensure the safety and security of vehicles [52, 53].



2.6 Role of Electric Mobility in the African Energy Transition

The African Union envisions a prosperous continent by 2063, achieved through industrialization, value addition, innovation, and the use of science and technology to promote social and economic development for shared prosperity [59]. However, Africa only accounted for 3% of the global new vehicle market in 2020, and the importation of old cars and an increasing number of vehicles are contributing to climate emissions and worsening air quality in the region [53].

A study revealed that approximately 1.5 million used cars are imported into Africa annually, and between 2010 and 2020, the demand for fossil fuels in the transportation industry increased by 50% [57]. Figure 5 illustrates that, based on current regulations, CO_2 emissions from cars (excluding 2 and 3-wheelers) will reach 909 million tonnes in 2050, or 2.3 times the 2020 figure [52]. However, a quick transition to zero-emission vehicles (ZEVs) in the region could cut CO_2 emissions by 53% by 2050 compared to 2020 levels [54]. The impact of EVs on the energy system varies significantly depending on factors such as the power generation mix [56]. Researchers have not extensively studied EV growth in African countries, particularly in sub-Saharan African nations such as Nigeria. Hence, there is no definitive answer on how EVs will affect the African energy transition [50-51].

3. Methodology

3.1. Study Area

The area of focus for this research is Sub-Saharan Africa (SSA), which consists of 49 countries in Africa, excluding the five North African countries of Morocco, Tunisia, Egypt, Algeria, and Libya [52]. According to the recent World Bank data review, SSA in numbers can be summarized in table 2 below.

Table 2. SSA in numbers (development, demographic, gender, energy, CO2 emission indices)

	SSA Development/Demographic/Gender/ Energy/ Emission Indices	Year	Value	Unit
1	Number of poor at $1.90 a day or less (2011 purchasing power parity - PPP)	2018	435.6	Million
2	The ratio of female to male labor force participation rate (modeled ILO estimate)	2021	84.67	%
3	CO2 emissions	2019	0.7442	metric tons per capita
4	Electric power consumption	2014	487.33	kWh per capita
5	Energy use	2014	687.23	kg of oil equivalent per capita
6	GDP annual growth	2021	4.127	%
7	Annual inflation, GDP deflator	2021	5.840	%
8	Population density	2022	47.551	people per sq. km of land area
9	Population, total	2021	1.17	Billion

It is important to note that these statistics may vary across different countries and regions within SSA, and should be interpreted with caution when making generalizations about the entire region. Adapted from the geospatial datasets [53-63], figure 5 shows the distribution of the major airports, ports, electricity grid, and road and rail networks in SSA.

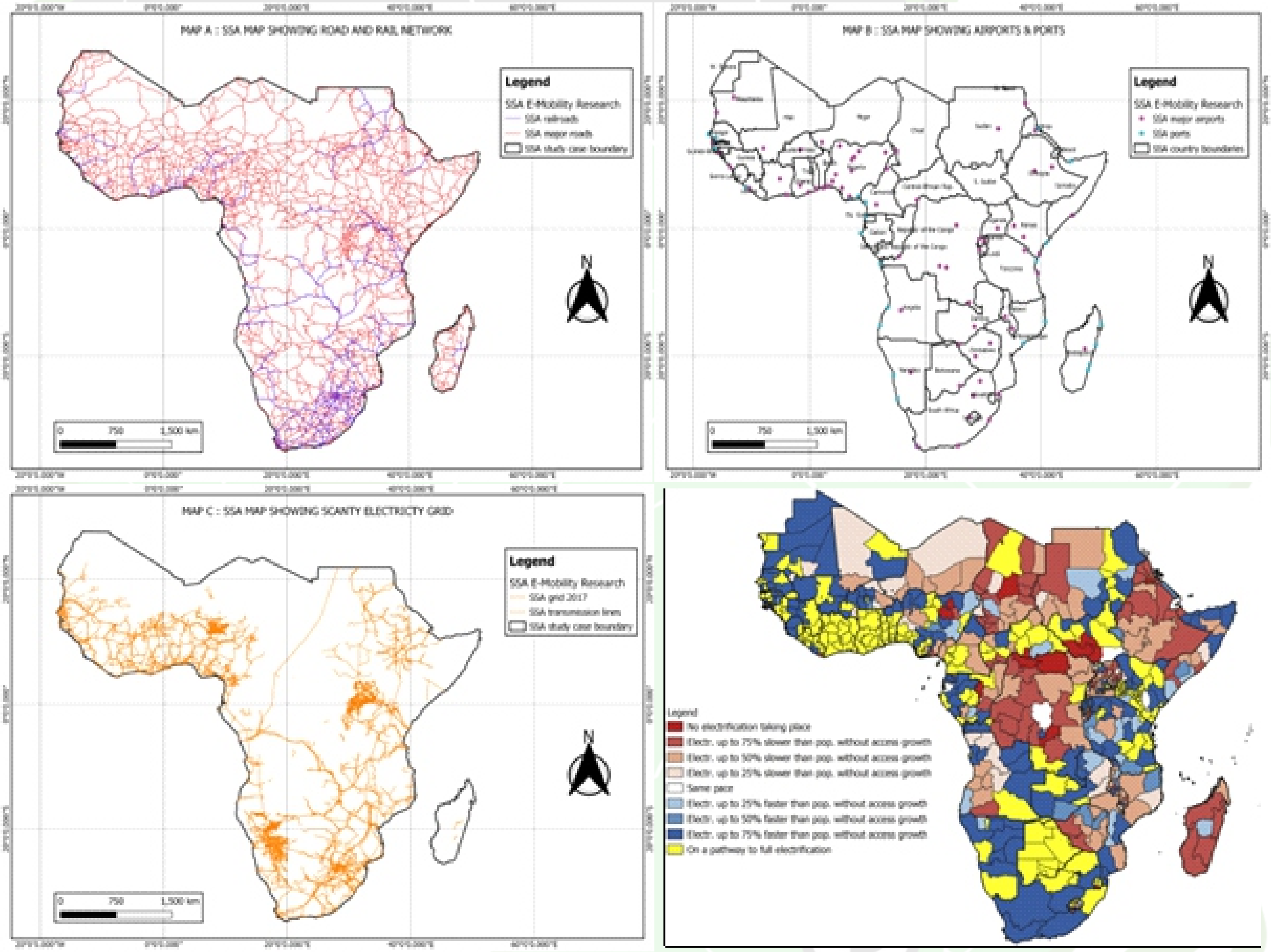


Figure 5: major airports, ports, electricity grid, road and rail networks, and country border distribution in a study focus area

3.2 Assumptions and Date Sources

The approach used in this study is based on an extensive review of global, regional, and Sub-Saharan Africa (SSA)-specific literature from reports and peer-reviewed publications. To collate data, various sources were utilized, including:

1. The United Nations Environment Programme (UNEP) electric mobility projects in SSA and lessons learned [64]
2. UNEP Copenhagen Climate Centre electric mobility market and policy readiness frameworks for Zimbabwe and Ghana [65],[66]
3. International Energy Agency (IEA) 2022 electric vehicle outlook report [4], [26]
4. Climate Compatible Growth (CCG) country-specific transport sector dataset [67]
5. Alternative Fuels Data Center [68]
6. Regulatory Indicators for Sustainable Energy (RISE) [69]
7. World Economic Outlook [70]
8. UNEP's Global Electric Vehicle Policy Database [71]
9. UNEP's eMob calculator [72]
10. Survey-based choice experiments

It is assumed that most SSA countries share similar characteristics, such as a political landscape, income level distribution, limited universal access, import-based fuel dependence, import-based automotive industry, unsustainable transport sector dominated by inefficient second-hand vehicles, and underdeveloped institutional capacity to establish robust and forward-looking policies and regulations. However, it is essential to note that there may be variations in these characteristics across different countries and regions within SSA.

3.3 Overview of Multi-Criteria Analysis

There is a significant interest in utilizing multi-criteria analysis to tackle complex problems across a wide range of fields. Multi-Criteria Decision Methods (MCDM) are commonly used in decision-making due to their ability to break down complex problems into simpler forms [73]. There are various approaches to MCDM, and these methods can be grouped into three main categories [74-75]:

- Value measurement models: These models involve constructing a numerical score for each alternative, and assigning a weight to each criterion that reflects its importance (e.g., Weighted Sum Model, Analytic Hierarchy Process).
- Goal, aspiration, and reference level models: These methods measure how well the alternatives achieve predetermined goals or aspirations (e.g., TOPSIS).
- Outranking models: These models compare the alternatives pairwise for each criterion, determining the strength of preference for one over the other (e.g., ELECTRE, PROMETHEE).

3.3.1. Analytic Hierarchy Process

The Analytical Hierarchy Process (AHP) is a widely adopted method in various research fields, owing to its simplicity and natural ease of use. It is often used to determine the preferences or weights of importance for criteria and alternatives. AHP offers several advantages, including the ability to use both quantitative and qualitative methods, a systematic approach to decision-making that allows for traceability of decisions, and consistency indices that ensure quality assurance. However, there are also challenges associated with this methodology. It can be a time-consuming exercise, and there is a risk of information loss due to the possibility of compensation effects between inconsistent scoring. Additionally, the complexity of the problem being solved, as determined by the number of criteria and alternatives, can pose difficulties [76]. It is worth noting that AHP can be used in combination with artificial neural networks and geographical information systems (GIS).

3.3.2. Weighted Sum Model

The Weighted Sum Model (WSM) is currently the most widely used and straightforward multiple-criteria decision-making method. Its primary characteristic is the intuitive algorithm of conduct it employs. Unlike AHP, where pairs of criteria are compared to determine priorities and assess preferences, WSM involves assigning weights to individual criteria and evaluating options across all criteria [77]. This model is primarily utilized in single-dimensional problems with limited data, but it still generates comparable results to more sophisticated models [78]. The simplicity of the WSM makes it attractive to decision-makers, and it also requires less data quality compared to more complex models. In some cases, it is used in combination with other models such as AHP [79], due to its easy applicability [80]. WSM is best suited for problems where all variables have the same physical dimensions and are based on the "additive utility" assumption [81]. However, for multidimensional problems involving qualitative and quantitative attributes, the challenge becomes more complex to handle because the hypothesis is violated, necessitating the application of normalization schemes [81].

3.3 Overview of Multi-Criteria Analysis - Cont.

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3.3.3. Topsis

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a straightforward and logical-mathematical approach that identifies the best alternative closest to the positive ideal solution (optimal solution) while being furthest from the negative ideal solution (inferior solution) [76]. This method determines the Euclidean distance of each alternative to both ideal solutions, and the best option is the one with the shortest distance to the positive ideal solution and the farthest distance from the negative ideal solution [78], both of which are hypothetical solutions. TOPSIS requires weight judgments only, and the relative distances depend on the weights and the range of alternatives, allowing for smoother trade-offs between the positive and negative ideal solutions [75]. However, for multi-dimensional problems, vector normalization is necessary, which can be a drawback of the method [76].

3.3.4. Promethee

The Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) is a method used for outranking, which is the process of determining the strength of one alternative over another. The PROMETHEE family methods rank alternatives by computing both a positive outranking flow and a negative outranking flow for each alternative. PROMETHEE I and II only allow for indifference when the flows between two alternatives are equal, and in cases where the flows are nearly equal, the alternative with the higher flow is preferred. PROMETHEE III is an improved version that allows for an interval of indifference to be defined for each alternative, making it a better reflection of the decision maker's behavior [79].

One of the main advantages of PROMETHEE is its ability to operate directly on variables without requiring normalization, even when there is missing information [78]. However, it can be time-consuming, and when dealing with many criteria, it can be challenging to maintain an overview of the problem [76]. Additionally, there is a possibility of rank reversal, where the ranking of alternatives may be reversed when a new alternative is introduced [74].

3.3.5. Electre

ELECTRE (ELimination Et Choice Translating REality) is another outranking method that uses pairwise comparison to select the most preferred alternative from among others. This approach is particularly suitable for decision problems with many alternatives but few criteria because it eliminates the least favorable alternative. However, ELECTRE has been criticized for its long computational process, which is more time-consuming than other techniques [75]. Additionally, it has a complex application, and there is a possibility that the method may not identify a preferred solution [78]. Nonetheless, the method can be applied even with missing information and under uncertainties [76]. Incomparability is a fundamental feature of any evaluation matrix because each alternative has both good and bad performances on some criteria. Without additional information, no sound mathematical theory can determine the best decision, so the final choice is left to the decision maker [76].

3.4 Vehicle Segment Prioritization

3.4.1. Prioritization Overview

The transport sector in SSA comprises various types of vehicles, including bicycles, motorcycles, loaders, passengers, light vehicle trucks, taxis, personal vehicles, heavy vehicle trucks, mini buses, and coach buses. To facilitate the adoption of electric mobility, prioritizing specific vehicle segments could help policy officials and legislators focus their efforts and resources. This would lead to a positive impact in the phased adoption and transition to electric mobility as future vehicle segments can benefit from lessons learned from the pioneering vehicle segments. The prioritization of vehicle segments for electric mobility adoption in SSA was carried out using both quantitative and qualitative data. The framework involves identifying prioritization criteria, assigning weights to the criteria, scoring, aggregating scores, and performing sensitivity analysis to check the impact of changes in assumption on the prioritization results.

To determine the weights for the prioritization criteria, consultations were held with local/regional experts, and interactions were made with various SSA government stakeholders. The validation of the weights was done through stakeholders' meetings, including the "Association for Electric Mobility & Development in Africa." Figure 6 below shows the vehicle prioritization framework adopted in this study.

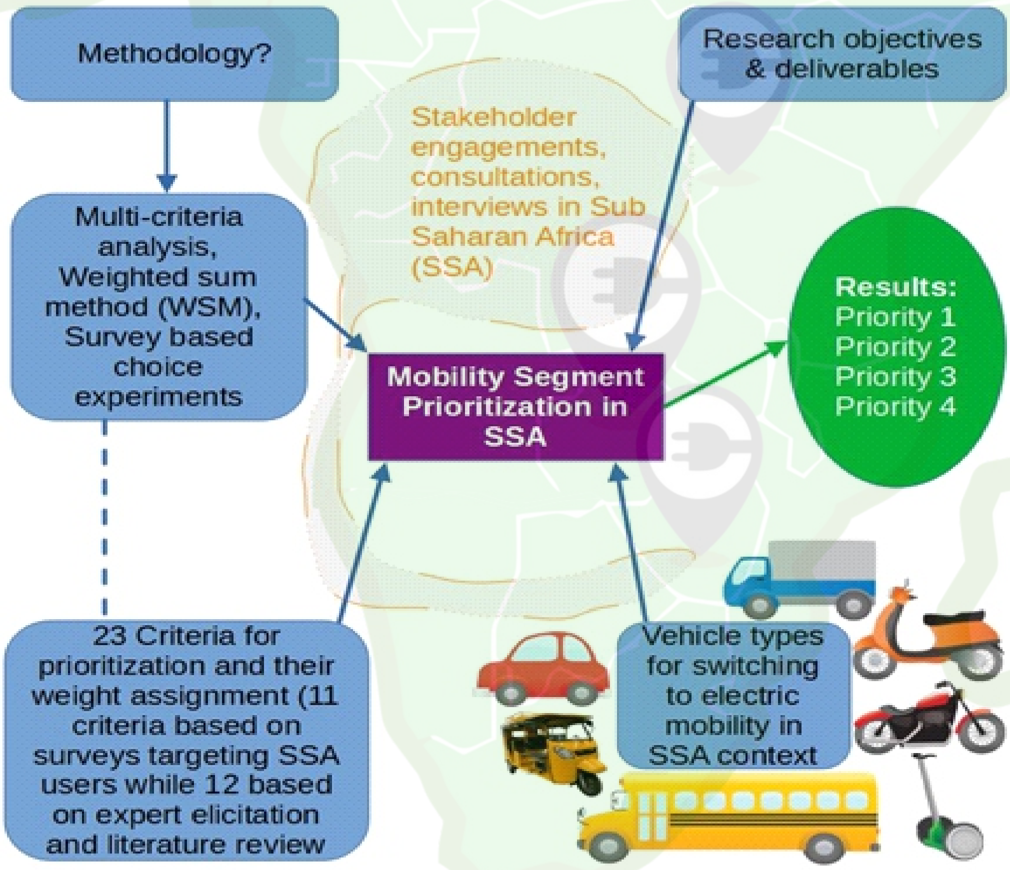


Figure 6. Vehicle Segment Prioritization Framework

3.4 Vehicle Segment Prioritization - Cont.

The criteria hierarchical levels and valuation methods adopted in the mobility segment prioritization framework are illustrated in Table 3.

Table 3. Vehicle segment prioritization criteria hierarchical levels and valuation methods

Criteria No.	Level 1	Level 2	Level 3	Valuation Method
EP:1	SSA Local Context	Government Support	Government preference	Government willingness to provide fiscal incentives
EP:2				Government willingness to provide technical support and non-fiscal incentives
EP:3		Supporting Ecosystem	Local EV model availability	Number of local EV dealerships
EP:4			Local spare parts availability and post-sales services	Existing local ecosystem; availability for ICE vehicle maintenance and repair
EP:5			Local supply potential for EV components, models, and assembly	Potential of supporting EV component industry and model assembly
EP:6			EV technical skills and R&D	Number of corporates and academic institutions and corporates conducting R&D in EVs
EP:7			Accessibility and quality of roads	Ease of navigating on roads of varying qualities (qualitative assessment)
EP:8		Usage Characteristics	Vehicle on-road stock	Vehicle stock in the percentage of the vehicle segment
EP:9			Vehicle trip length	Vehicle segment average trip length per year (km)

3.4 Vehicle Segment Prioritization - Cont.

The details of the weight assignment and ranking of the 23 prioritization criteria highlighted in Figure 6 are presented under the methodology application section (section 4).

3.4.2.Survey

As part of the methodology, a web-based survey was developed due to its cost-effectiveness, efficiency, and the limited time available to conduct the study. The survey aimed to determine the EV category to prioritize in the SSA region among the following: 2-wheelers (bicycles and motorcycles), 3-wheelers (loaders and passengers), 4-wheelers (light vehicle trucks, taxis, and personal), heavy vehicle trucks, minibuses, and coach buses. The survey was conducted using JotForm facilities at https://form.jotform.com/221974400647558 from June 1, 2022, to July 31, 2022. It consisted of 11 multiple-choice questions and 3 general questions. The multiple-choice questions had 8 answer options, providing respondents with ample latitude to select the appropriate answer. Under the general question, respondents had the option to provide general comments or further insights to enhance the study.

3.4 Vehicle Segment Prioritization - Cont.

3.4.5.Normalization and Aggregation

In terms of the criteria used in the survey, a qualitative assignment array was initially used, with categories such as "Very High," "High," "Moderate," "Low-Moderate," "Low," "Very Low," "Extremely Low," and "Not Applicable." Later on, these categories were converted to percentage values by using a representative ranking scale of 1 to 8. To normalize the qualitative priorities equation 1 below was utilized.

$$N(\%)_{(8<n<1)} = N_{(n-1)} - \frac{N_{VH} - N_{NA}}{|Rank_{(VHP)} - Rank_{(NA)}|} for\ n \in A, Rank \in B ---------(1)$$

Where: 'A' is a set of whole numbers between 1 and 8

'B' is a set of whole numbers between 0 and 9

(N_{VHP}) is a fixed normalized value of 100% to mean very high priority

(N_{NA}) is fixed at 0% to denote priority not applicable to any region or country in Sub-Saharan Africa.

($Rank_{VHP}$) is the rank a very high priority

($Rank_{NA}$) is the rank when the priority is not applicable

To normalize the literature-based measurement scores equation 2 below was utilized.

$$Y_i = [(X_i + F(X)) / ((X) - (X))] \times 100\%. ----------------- (2)$$

Where: Y_i is the normalized value in percentage.

Where X is an array of entries tallying with the criteria measurement score of each vehicle segment (i.e., an of seven entries in this case).

X_i = - X_i and F(X) = max(X) if the objective is to optimize a low value of X which becomes the benchmarking score (i.e., fuel efficiency per passenger-km liter/ pax-km).

X_i = X_i and F(X) =- min(X) if the objective is to optimize a high value of X which becomes the benchmarking score (i.e., percentage of vehicle on-road stock).

3.4 Vehicle Segment Prioritization - Cont.

The weighted sum which is an aggregation of all the weights and individual scores is obtained by applying equation 3 below.

$$A_j^{WSM} = \sum_{j=1}^{N} \prod_{k=1}^{3} L_{j,k} \left\{ (I_{Lit}^{s} = Y_i) + \sum (N(s) \times I_{Sur}^{s}) \right\} ------------(3)$$

Where: A_j^{WSM} *is the weighted sum for each vehicle segment*

$L_{j,k}$ *is the product of the weight of the criteria levels.*

I_{Lit}^{s} *is the individual scoring of criteria based on literature & is equivalent to equation (2)*

$N(s)$ *is the normalized score value in percentage*

I_{Sur}^{s} *is the individual scoring of criteria in % based on the study survey report*

3.5. Barrier Analysis Famework

The framework takes into account the entire value chain of electric mobility, from vehicle manufacturing to disposal, to address all the barriers hindering its adoption in SSA. The identification of critical barriers using this framework can assist African governments in SSA to determine appropriate measures such as policies and strategies to facilitate the large-scale deployment of electric mobility in the region. The vehicle value chain depicted in Figure 7 informs the criteria for analyzing barriers.

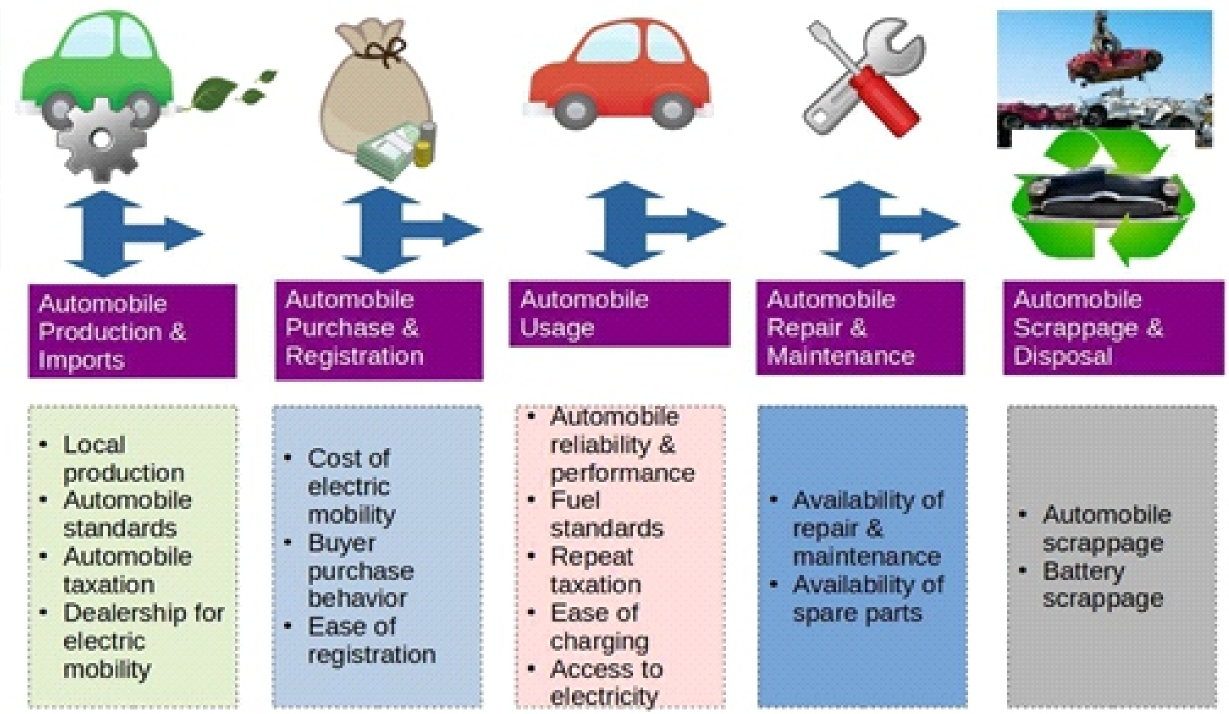


Figure 7. The Vehicle Value Chain feeding into Barrier Analysis Framework

3.5. Barrier Analysis Famework - Cont.

The barriers for analysis were selected based on the results of the vehicle segment prioritization discussed in section 3.3. Then, the categories and criteria for actual barriers were streamlined by adapting the approach used in reports from the United Nations Environment Programme (UNEP) on Electric Mobility Projects in Africa, as well as reports from Zimbabwe and Ghana's Electric Mobility Policy Framework of 2022 [64], [65], [80], [81]. The comprehensive barrier analysis method is presented in Figure 8.

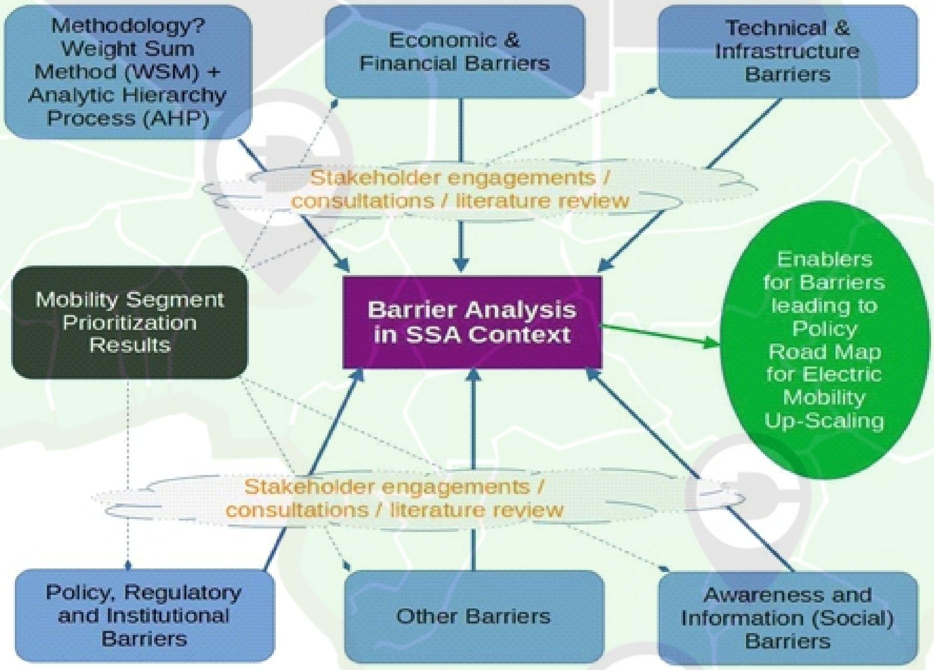


Figure 8. Barrier Analysis Framework

3.5. Barrier Analysis Famework - Cont.

The main barrier criteria and sub -criteria under consideration impeding the deployment of electric mobility are summarized in Table 4.

Table 4. Main barrier criteria and sub-criteria

	Barrier Criteria Distribution				
Main Criteria	***Economic***	***Infrastructure***	***Policy***	***Social***	***Technical***
Sub-Criteria	High purchase cost	Insufficient charging stations	Lack of government's long-term planning & goals	Mistrust & lack of knowledge of EVs	Limited range
	Battery replacement cost	Cost of charging or construction charging infrastructure	Vague or absent tax exemptions	Lack of environmental awareness & doubt environmental benefits of EVs	Lack of evidence on performance and reliability
	Rising electricity cost for charging	Long charging time	Lack of awareness creation about EVs	Limited understanding of the quality & safety of EVs	Limited battery life
	Lack of credit access for EVs	Unreliable power supply			Fewer EV models
		The problem of battery disposal & risk of battery degradation			Lack of capacity for maintenance and repairs
		Insufficient repair & maintenance workshops			
		Insufficient to the non-existence of local industries			

3.5. Barrier Analysis Famework - Cont.

3.5.1. Barrier analysis using AHP

The AHP methodology was utilized to evaluate and prioritize the obstacles to electric vehicle (EV) adoption in Africa. As described earlier, this approach involves breaking down complicated multi-criteria decision-making (MCDM) problems into smaller components, which creates a hierarchical framework for the issue at hand. Subsequently, Saaty's pairwise comparison procedure is employed to each level of the hierarchical framework. The process applied is depicted in figure 9 as follows:

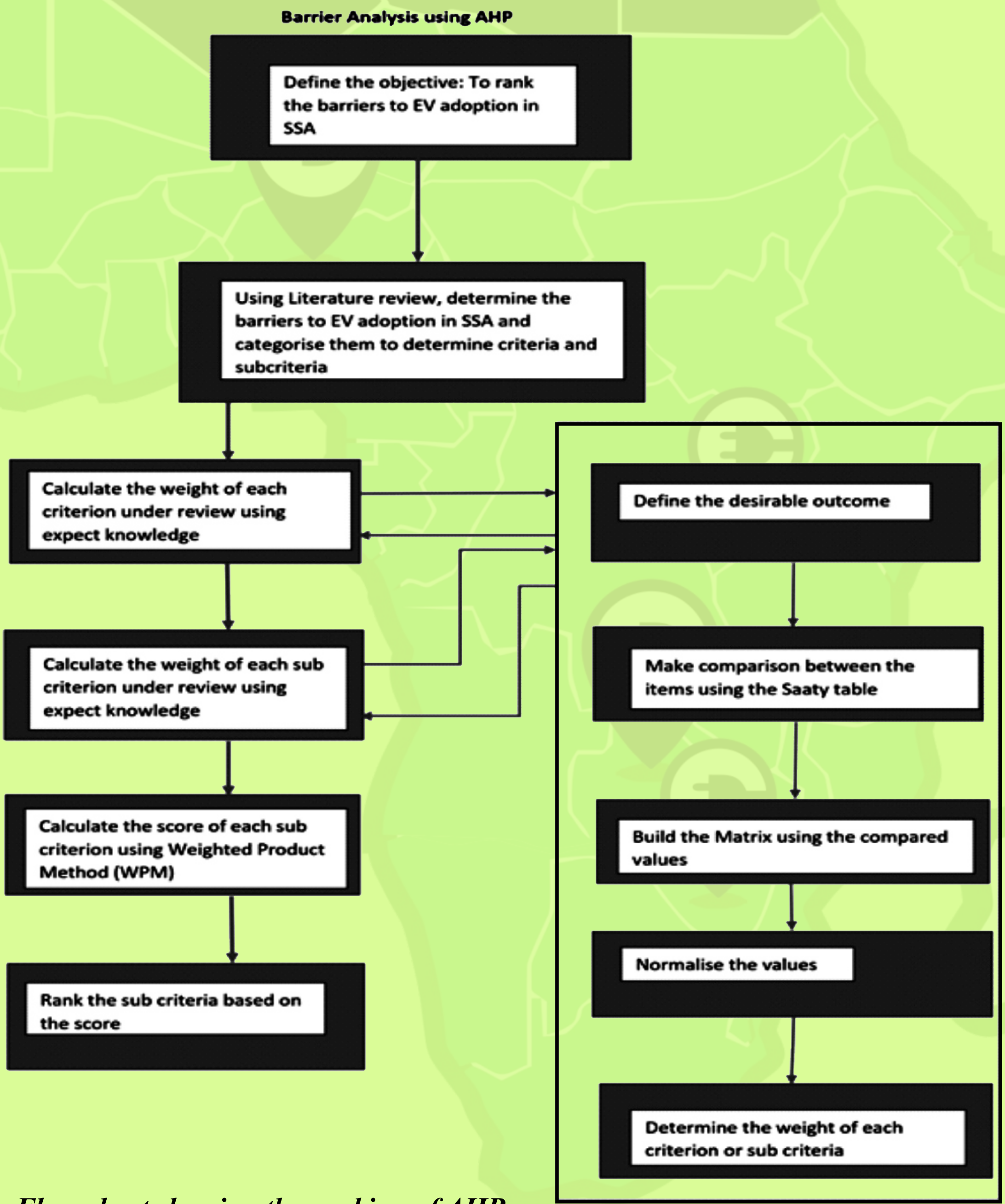


Figure 9. Flow chart showing the ranking of AHP

3.5. Barrier Analysis Famework - Cont.

To begin with, the main objective was to prioritize the obstacles to the adoption of electric vehicles in SSA. To achieve this, a three-tier hierarchy was created, with the goal at the topmost level (level 1), criteria at the second level (level 2), and sub-criteria at the bottom level (level 3). To conduct pairwise comparisons of both the criteria and sub-criteria, Table 5, also known as the table of Saaty, was utilized.

Table 5. showing priorities in pairwise comparison as defined by Professor Saaty[79]

Value	**Definition**
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	can be used to express intermediate values

The next step was to construct the pairwise comparison matrix (Saaty's matrix) for both the main criteria and sub-criteria. Saaty's matrix $A = \{a_{ij}\}$ was defined where a_{ij} represent the intensity of the preference between objects (criteria and sub-criteria items) c_i and c_j. If the object c_i in the row is more important than c_j in the column, then $a_{ij} \in \{1, 2, 3, 4, 5, 6, 7, 8, 9\}$, else $a_{ij} = \frac{1}{a_{ij}}$ as shown below [79]:

$$\begin{array}{c c} & \begin{array}{cc} c_i & c_j \end{array} \\ \begin{array}{c} c_i \\ c_j \end{array} & \begin{pmatrix} 1 & a_{ij} \\ \frac{1}{a_{ji}} & 1 \end{pmatrix} \end{array}$$

Where c_i, c_j are criteria or sub-criteria; a_{ij}, $\frac{1}{a_{ji}}$ express the intensity of the preference between the objects c_i, c_j using Saaty's scale.

The next step in the process was to get the weights for both the criteria and sub-criteria based on the calculation of the eigenvector matrix [79] :

$$A.\gamma = \lambda_{max}.\gamma$$

Where A is Saaty's matrix, γ is the eigenvector of Saaty's matrix and λ_{max} is the largest eigenvalue of Saaty's matrix. It is important to note that the eigenvector matrix must be standardized using the geometric mean method [79]:

$$D_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}} \quad (5)$$

Where D_i is the geometric mean expressing the weight of criteria or sub criteria, n is the number of criteria or sub-criteria, a_{ij} are the elements of Saaty's matrix.

The last step is to calculate the final score of each sub-criteria using the Weighted Product Method and consequently to get the rank of the barriers to EV adoption in SSA.

3.5.2. Modeling Costs, Energy Use, and Carbon Emissions

This The framework described below, with a focus on Gasoline, diesel, gasoline hybrid electric (HEV), gasoline plug in hybrid electric (PHEV), all electric vehicle (EV), Gaseous hydrogen (G.H2) fuel cell vehicle (FCV) propulsion types, is based on the AFLEET Tool module within the Argonne GREET Software Model. While originally developed for the United States, the model has been adapted for Sub Saharan Africa with updated data on various factors such as electrical grid mix, emission factors, inflation, interest rates, depreciation, annual vehicle miles traveled, fuel costs, and vehicle costs [83]. The study employs four assessment methods to model the impacts of electric mobility adoption, namely cost implications, energy use, carbon footprint emissions, and air pollutant analysis. These assessment methods are summarized below and depicted in Figure 10 to facilitate understanding.

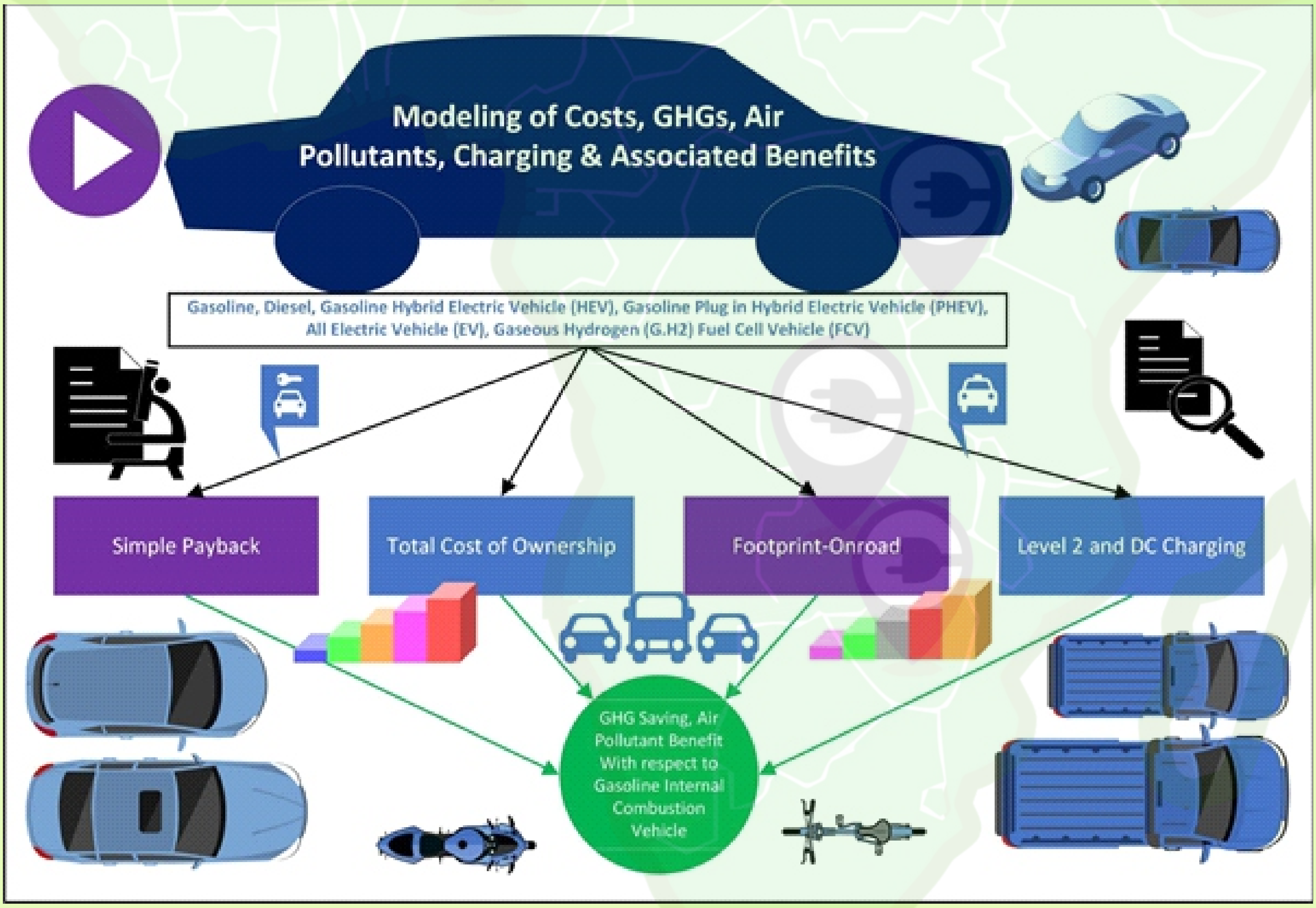
a) In the context of Sub-Saharan Africa, the Simple Payback approach is utilized to model the cost-effectiveness of on-road vehicles. This method entails analyzing the expenses associated with acquiring and operating a new AFV (Alternative Fuel Vehicle) designed for either on road or off-road use and comparing them to those of its conventional counterpart. Additionally, the approach factors in the average annual consumption of petroleum, greenhouse gas (GHG) emissions, and air pollutant emissions.

3.5. Barrier Analysis Famework - Cont.

a) For the purpose of modeling on-road vehicles, the Total Cost of Ownership (TCO) approach is utilized. This method involves assessing the net present value of both operating and fixed costs over the course of a new vehicle's planned ownership, as well as considering the lifetime consumption of petroleum, greenhouse gas (GHG) emissions, and air pollutant emissions.

b) The On-Road Vehicle Fleet Footprint approach is used to estimate the yearly petroleum consumption, greenhouse gas (GHG) emissions, and air pollutant emissions of both current and new on-road vehicles. This method considers the fact that older vehicles usually have higher rates of air pollutant emissions than newer vehicles.

c) The Electric Vehicle Charging approach is employed to calculate the yearly petroleum consumption, greenhouse gas (GHG) emissions, and air pollutant advantages that arise from the use of public electric vehicle charging infrastructure.



3.6. Method Limitations

Prioritization:

- The priorities of countries in Sub-Saharan Africa are diverse. For instance, 2 and 3 wheelers dominate the current fleets of East Africa and West Africa, while they are not as dominant in Southern Africa.
- The methodology relied heavily on a literature review, which resulted in some data being based on assumptions rather than interactions with country experts and government officials.
- The evaluation method used qualitative analysis, which is subjective in nature, therefore, there is a need for validation through sensitivity analysis.

Barrier Analysis:

- The pairwise comparisons on the Analytic Hierarchy Process (AHP) used in the barrier analysis are subjective, which may lead to inconsistency in decision-making.
- The methodology also relied heavily on a literature review, which means there was limited interaction with country experts and government officials.

AFLEET Tool:

- One limitation of using the AFLEET Tool in a peer-reviewed research methodology in the Zambian context is that the tool was developed specifically for the United States. Therefore, assumptions, such as emission factors for greenhouse gases and air pollutants, may not be suitable for Zambia's unique transportation sector.

4. Results and Analysis

4.1. Vehicle Segmentation Prioritization

This section pertains to the application of the vehicle segment prioritization framework. In this framework, 23 criteria were utilized to rank the seven vehicle segments that were being considered. The vehicle segments included 2-wheeler personal, 2-wheeler delivery, 3-wheeler taxi, 4-wheeler personal, 4-wheeler taxi, minibus, and coach bus. Table 3 presented each criterion, which consisted of three levels of weight assignment. The final weight values were determined through comprehensive stakeholder engagement and expert judgment, resulting in an overall weightage ranging from 0 to 100 percent. To rank or prioritize the vehicle segments, the weighted sum of the overall weight of each criterion was computed. This was achieved by multiplying the weights for the three criteria levels with the individual scores acquired from the study survey and values obtained from literature.

4.1.1.Criteria Weight Assignment

Table 6 displays the weights assigned to each level of the 23 criteria used in the study. These weights were determined through a rigorous process involving stakeholder engagement and expert judgment from various entities such as energy and transport regulators/ministries in Sub Saharan Africa (SSA), private sector, electric utilities, universities including the University of Zambia, Copperbelt University, University of Zimbabwe, Association for Electric Mobility & Development in Africa, United Nations Environment Programme, University of Edinburgh, University of Strathclyde, University of Rwanda, Luleå University of Technology, and others.

Table 6: Criteria weight assignment for the three levels

Criteria No.	Criteria Levels			Weightage		
	Level 1 (L1)	Level 2 (L2)	Level 3 (L3)	L1(%)	L2(%)	L3(%)
EP:1	SSA Local Context	Government Support	Government preference	30%	45%	70%
EP:2						30%
EP:3		Supporting Ecosystem	Local EV model availability		20%	15%
EP:4			Local spare parts availability and post-sales services			20%
EP:5			Local supply potential for EV components, models and assembly			25%
EP:6			EV technical skills and R&D			25%
EP:7			Accessibility and quality of roads			15%
EP:8		Usage Characteristics	Vehicle on-road stock		35%	10%
EP:9			Vehicle trip length			30%
EP:10			Fuel consumption per passenger-km			30%
EP:11			EV charging easiness			30%
EP:12	Costs	Capital Expenditure (CAPEX)	Investment requirements of EVs	35%	70%	75%
EP:13			Investment requirements of charging infrastructure			25%
EP:14		Operational Expenditure (OPEX)	Electricity tariff (costs)		30%	40%
EP: 15			O&M cost saving potential			60%
EP:16	Benefits	Economic benefits	Total cost of ownership (TCO)	35%	30%	35%
EP:17			Potential of retrofitting ICE vehicle to EV			15%
EP:18			Fuel savings			50%
EP:19		Social benefits	Opportunities for creating jobs		20%	33.4%
EP:20			Equity and quality of life			33.3%
EP:21			Gender equality			33.3%
EP:22		Local pollution reduction benefits	Air pollution reduction potential		15%	100%
EP:23		Climate benefits	GHG reduction potential		35%	100%

4.1.2. Survey Based Individual Scores

Table 7 shows the individual scores for the 11 criteria based on the jotform.com survey report [81].

Table 7: Results from survey-based scoring for 11 criteria (EP:1, EP:2, EP:3, EP:4, EP:5, EP:6, EP:7, EP:11, EP:18, EP:19, EP:20)

EP:1	**Government willingness to provide fiscal incentives**							
Priority	**Rank**	**Normalize**	**2W-Personal**	**2W-Delivery**	**3W-Taxi**	**4W-Personal**	**4W-Taxi**	**Mini-Bus**
Very High	1	100%	12.6%	11.8%	6.9%	17.5%	15.8%	17.8%
High	2	86%	14.6%	19.6%	14.9%	18.4%	19.8%	37.6%
Moderate	3	71%	20.4%	22.5%	31.7%	33.0%	38.6%	28.7%
Low - Moderate	4	57%	23.3%	23.5%	12.9%	11.7%	14.9%	6.9%
Low	5	43%	17.5%	9.8%	11.9%	7.8%	3.0%	4.0%
Very Low	6	29%	2.9%	5.9%	6.9%	6.8%	4.0%	4.0%
Extremely Low	7	16%	7.8%	5.9%	12.9%	4.9%	4.0%	1.0%
Not Applicable	8	0%	1.0%	1.0%	2.0%	0.0%	0.0%	0.0%
EP:2	**Government willingness to provide technical support and non-fiscal incentives**							
Priority	**Rank**	**Normalize**	**2W-Personal**	**2W-Delivery**	**3W-Taxi**	**4W-Personal**	**4W-Taxi**	**Mini-Bus**
Very High	1	100%	3.0%	5%	2.0%	7.0%	7.9%	12.0%
High	2	86%	17.0%	15%	15.0%	23.0%	25.7%	37.0%
Moderate	3	71%	27.0%	29%	34.0%	33.0%	34.7%	26.0%
Low - Moderate	4	57%	21.0%	23%	17.0%	12.0%	8.9%	8.0%
Low	5	43%	14.0%	10%	12.0%	9.0%	8.9%	6.0%
Very Low	6	29%	6.0%	7%	5.0%	7.0%	5.9%	5.0%
Extremely Low	7	16%	10.0%	9%	11.0%	9.0%	7.9%	6.0%
Not Applicable	8	0%	2.0%	2%	4.0%	0.0%	0.0%	0.0%
EP:3	**Local EV model availability**							
Priority	**Rank**	**Normalize**	**2W-Personal**	**2W-Delivery**	**3W-Taxi**	**4W-Personal**	**4W-Taxi**	**Mini-Bus**
Very High	1	100%	5.0%	5.0%	6.0%	4.9%	4.0%	4.0%
High	2	86%	10.9%	8.0%	4.0%	9.8%	13.0%	8.0%
Moderate	3	71%	15.8%	19.0%	19.0%	22.5%	19.0%	20.0%
Low - Moderate	4	57%	15.8%	16.0%	16.0%	13.7%	14.0%	16.0%
Low	5	43%	11.9%	10.0%	10.0%	12.7%	11.0%	14.0%
Very Low	6	29%	9.9%	13.0%	10.0%	8.8%	10.0%	6.0%
Extremely Low	7	16%	20.8%	20.0%	23.0%	21.6%	23.0%	24.0%
Not Applicable	8	0%	9.9%	9.0%	12.0%	5.9%	6.0%	8.0%
EP:4	**Local spare parts availability and post-sales services**							
Priority	**Rank**	**Normalize**	**2W-Personal**	**2W-Delivery**	**3W-Taxi**	**4W-Personal**	**4W-Taxi**	**Mini-Bus**
Very High	1	100%	9.9%	10.9%	5.9%	9.7%	8.9%	13.9%
High	2	86%	15.8%	15.8%	12.9%	16.5%	20.8%	14.9%
Moderate	3	71%	23.8%	21.8%	22.8%	24.3%	19.8%	20.8%
Low - Moderate	4	57%	14.9%	15.8%	17.8%	15.5%	17.8%	15.8%
Low	5	43%	5.9%	5.0%	6.9%	7.8%	6.9%	7.9%

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Very Low	6	29%	2.0%	3.0%	3.0%	2.9%	2.0%	2.0%
Extremely Low	7	16%	20.8%	19.8%	21.8%	19.4%	19.8%	20.8%
Not Applicable	8	0%	6.9%	7.9%	8.9%	3.9%	4.0%	4.0%
EP:5	**Local supply potential for EV components, models and assembly**							
Priority	**Rank**	**Normalize**	**2W-Personal**	**2W-Delivery**	**3W-Taxi**	**4W-Personal**	**4W-Taxi**	**Mini-Bus**
Very High	1	100%	9.0%	11.0%	8.0%	6.0%	9.0%	7.9%
High	2	86%	13.0%	13.0%	11.0%	14.0%	15.0%	16.8%
Moderate	3	71%	23.0%	20.0%	23.0%	28.0%	25.0%	23.8%
Low - Moderate	4	57%	13.0%	15.0%	15.0%	11.0%	14.0%	15.8%
Low	5	43%	11.0%	9.0%	11.0%	11.0%	9.0%	7.9%
Very Low	6	29%	11.0%	11.0%	9.0%	11.0%	9.0%	10.9%
Extremely Low	7	16%	13.0%	14.0%	15.0%	15.0%	15.0%	12.9%
Not Applicable	8	0%	7.0%	7.0%	8.0%	4.0%	4.0%	4.0%
EP:6	**EV technical skills and R&D**							
Priority	**Rank**	**Normalize**	**2W-Personal**	**2W-Delivery**	**3W-Taxi**	**4W-Personal**	**4W-Taxi**	**Mini-Bus**
Very High	1	100%	5.9%	6.0%	4.0%	9.0%	8.0%	8.0%
High	2	86%	14.9%	18.0%	8.0%	16.0%	16.0%	13.0%
Moderate	3	71%	12.9%	10.0%	21.0%	17.0%	19.0%	24.0%
Low - Moderate	4	57%	20.8%	26.0%	23.0%	23.0%	24.0%	23.0%
Low	5	43%	16.8%	12.0%	15.0%	12.0%	11.0%	7.0%
Very Low	6	29%	5.0%	5.0%	5.0%	7.0%	6.0%	7.0%
Extremely Low	7	16%	19.8%	19.0%	18.0%	15.0%	14.0%	15.0%
Not Applicable	8	0%	4.0%	4.0%	6.0%	1.0%	2.0%	3.0%
EP:7	**Accessibility and quality of roads**							
Priority	**Rank**	**Normalize**	**2W-Personal**	**2W-Delivery**	**3W-Taxi**	**4W-Personal**	**4W-Taxi**	**Mini-Bus**
Very High	1	100%	11.0%	13.0%	5.0%	12.9%	12.0%	14.9%
High	2	86%	31.0%	23.0%	16.0%	26.7%	27.0%	28.7%
Moderate	3	71%	23.0%	32.0%	42.0%	35.6%	42.0%	35.6%
Low - Moderate	4	57%	16.0%	14.0%	14.0%	10.9%	7.0%	10.9%
Low	5	43%	9.0%	7.0%	8.0%	5.9%	5.0%	6.9%
Very Low	6	29%	1.0%	2.0%	2.0%	1.0%	4.0%	1.0%
Extremely Low	7	16%	7.0%	6.0%	8.0%	5.0%	2.0%	2.0%
Not Applicable	8	0%	2.0%	3.0%	5.0%	2.0%	1.0%	0.0%
EP:11	**EV charging easiness**							
Priority	**Rank**	**Normalize**	**2W-Personal**	**2W-Delivery**	**3W-Taxi**	**4W-Personal**	**4W-Taxi**	**Mini-Bus**
Very High	1	100%	12.0%	12.0%	9.0%	8.9%	8.0%	7.0%
High	2	86%	16.0%	16.0%	15.0%	8.9%	10.0%	10.0%
Moderate	3	71%	12.0%	14.0%	15.0%	19.8%	23.0%	22.0%
Low - Moderate	4	57%	11.0%	11.0%	13.0%	15.8%	10.0%	12.0%
Low	5	43%	5.0%	3.0%	3.0%	4.0%	7.0%	7.0%
Very Low	6	29%	11.0%	12.0%	9.0%	14.9%	12.0%	12.0%
Extremely Low	7	16%	25.0%	25.0%	27.0%	22.8%	25.0%	26.0%
Not Applicable	8	0%	8.0%	7.0%	9.0%	5.0%	5.0%	4.0%
EP:18	**Opportunities for creating jobs**							

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Priority	Rank	Normalize	2W-Personal	2W-Delivery	3W-Taxi	4W-Personal	4W-Taxi	Mini-Bus
Very High	1	100%	25.7%	38.0%	31.0%	19.0%	38.0%	45.0%
High	2	86%	16.8%	21.0%	19.0%	23.0%	30.0%	24.0%
Moderate	3	71%	29.7%	23.0%	27.0%	32.0%	22.0%	25.0%
Low - Moderate	4	57%	8.9%	6.0%	7.0%	16.0%	7.0%	3.0%
Low	5	43%	8.9%	4.0%	6.0%	4.0%	0.0%	0.0%
Very Low	6	29%	3.0%	1.0%	1.0%	3.0%	1.0%	1.0%
Extremely Low	7	16%	5.0%	5.0%	5.0%	3.0%	2.0%	2.0%
Not Applicable	8	0%	2.0%	2.0%	4.0%	0.0%	0.0%	0.0%
EP:19	**Equity and quality of life**							
Priority	**Rank**	**Normalize**	**2W-Personal**	**2W-Delivery**	**3W-Taxi**	**4W-Personal**	**4W-Taxi**	**Mini-Bus**
Very High	1	100%	12.0%	14.9%	13.0%	20.6%	21.8%	21.0%
High	2	86%	26.0%	26.7%	23.0%	29.4%	34.7%	36.0%
Moderate	3	71%	32.0%	21.8%	24.0%	24.5%	22.8%	19.0%
Low - Moderate	4	57%	7.0%	14.9%	16.0%	10.8%	7.9%	10.0%
Low	5	43%	6.0%	6.9%	6.0%	4.9%	5.0%	4.0%
Very Low	6	29%	5.0%	4.0%	6.0%	3.9%	3.0%	4.0%
Extremely Low	7	16%	7.0%	5.9%	5.0%	2.9%	2.0%	3.0%
Not Applicable	8	0%	5.0%	5.0%	7.0%	2.9%	3.0%	3.0%
EP:20	**Gender equality**							
Priority	**Rank**	**Normalize**	**2W-Personal**	**2W-Delivery**	**3W-Taxi**	**4W-Personal**	**4W-Taxi**	**Mini-Bus**
Very High	1	100%	5.0%	5.0%	5.0%	11.0%	9.0%	7.0%
High	2	86%	13.0%	12.0%	12.0%	21.0%	20.0%	20.0%
Moderate	3	71%	28.0%	25.0%	23.0%	32.0%	27.0%	24.0%
Low - Moderate	4	57%	13.0%	16.0%	18.0%	12.0%	16.0%	14.0%
Low	5	43%	11.0%	10.0%	9.0%	7.0%	10.0%	10.0%
Very Low	6	29%	4.0%	7.0%	5.0%	2.0%	3.0%	4.0%
Extremely Low	7	16%	19.0%	18.0%	18.0%	10.0%	10.0%	15.0%
Not Applicable	8	0%	7.0%	7.0%	10.0%	5.0%	5.0%	6.0%

1.1.1. Literature Based Individual Scores

Table 8 shows the individual scores for the remainder of the 12 criteria based on extensive literature review in SSA.

Table 8: Results for the 11 criteria based on data from literature in

SSA (EP:8, EP:9, EP:10, EP:12, EP:13, EP:14, EP:15, EP:16, EP:17, EP:21, EP:22) [82]

No.	Measurement	2W-Personal	2W-Delivery	3W-Taxi	4W-Personal	4W-Taxi	Mini-Bus	Coach Bus
EP:8	Vehicle on-road stock (%) [3]	5%	40%	10%	8%	8%	18%	11%
	Normalize	0.0%	100.0%	14.3%	8.6%	8.6%	37.1%	17.1%
EP:9	Vehicle segment average trip length per year	25	130	25	40	100	200	200

	(km) [4]							
	Normalize	0.0%	60.0%	0.0%	8.6%	42.9%	100.0%	100.0%
EP:10	Vehicle segment fuel efficiency per passenger km (litre/ pax-km) [4]	0.02	0.02	0.03	0.05	0.02	0.01	0.01
	Normalize	75.0%	75.0%	50.0%	0.0%	75.0%	100.0%	100.0%
EP:12	Investment requirements of EVs [4]	2544	2544	3893	74635	74635	94643	117593
	Normalize	100.0%	100.0%	98.8%	37.3%	37.3%	19.9%	0.0%
EP:13	Investment requirements of charging infrastructure [4]	100	100	150	250	300	600	850
	Normalize	100.0%	100.0%	93.3%	80.0%	73.3%	33.3%	0.0%
EP:14	Electricity costs are indicated for running 100% EVs (in 2023) in each vehicle segment (Consumption in kWh*cost/kWh) [4, 5]	0.07	0.07	0.25	0.4	1.2	5	20
	Normalize	100.0%	100.0%	99.1%	98.3%	94.3%	75.3%	0.0%
EP:15								
EP:16	The ratio of TCO of a new EV to an existing ICE vehicle in each vehicle segment [4]	0.5	0.5	0.8	1	1	1.6	1.3
	Normalize	0.0%	0.0%	27.3%	45.5%	45.5%	100.0%	72.7%
EP:17	The ratio of TCO of a retrofitted EV to a new EV in each vehicle segment [4]	0.9	0.9	0.8	0.7	0.7	1	1
	Normalize	33.3%	33.3%	66.7%	100.0%	100.0%	0.0%	0.0%
EP:18	Fuel-saving potential with 100% EVs (in 2023) in each vehicle segment [4]	0.54	2.83	1.56	4	10	20	50
	Normalize	0.0%	4.6%	2.1%	7.0%	19.1%	39.3%	100.0%
EP:22	Percent of particulate matter (PM) reduction with 100% EVs (in 2023) in each vehicle segment [4, 6]	2.5	13	2.5	2.28	5.7	39.2	39.2

	Normalize	0.6%	29.0%	0.6%	0.0%	9.3%	100.0%	100.0%
EP:23	Percent of GHG emission reduction with 100% EVs (in 2023) in each vehicle segment [7-9]	4	4	3	2	2	1	1
	Normalize	0.0%	0.0%	33.3%	66.7%	66.7%	100.0%	100.0%

4.1.4. Vehicle Segment Ranking

The vehicle segment ranking is based on the weighted sum of the "product of the three criteria levels" in table 6 and that of the "criteria individual scores" in tables 7 and 8. Table 9 summarizes the prioritization and ranking for the 7 vehicle mobility segments.

4. Results and Analysis - Cont.

Table 9: Vehicle segment ranking from weighted sum method application

Criteria No.	Criteria Level Weightage				Overall Weight*Individual Score						
	L1(%)	L2(%)	L3(%)	Overall(%)	2Wheeler **Personal**	2Wheeler **Delivery**	3Wheeler **Taxi**	4Wheeler **Personal**	4Wheeler **Taxi**	Mini **Bus**	Coach **Bus**
EP:1	30%	45%	70%	9.45%	5.90%	6.13%	5.53%	6.57%	6.79%	7.32%	7.07%
EP:2			30%	4.05%	2.35%	2.40%	2.31%	2.60%	2.69%	2.90%	2.93%
EP:3		20%	15%	0.90%	0.41%	0.41%	0.38%	0.43%	0.43%	0.41%	0.42%
EP:4			20%	1.20%	0.66%	0.66%	0.60%	0.68%	0.69%	0.69%	0.67%
EP:5			25%	1.50%	0.81%	0.81%	0.78%	0.81%	0.84%	0.85%	0.83%
EP:6			25%	1.50%	0.77%	0.79%	0.74%	0.86%	0.86%	0.85%	0.84%
EP:7			15%	0.90%	0.61%	0.61%	0.56%	0.64%	0.65%	0.67%	0.65%
EP:8		35%	10%	1.05%	0.00%	1.05%	0.15%	0.09%	0.09%	0.39%	0.18%
EP:9			30%	3.15%	0.00%	1.89%	0.00%	0.27%	1.35%	3.15%	3.15%
EP:10			30%	3.15%	2.36%	2.36%	1.58%	0.00%	2.36%	3.15%	3.15%
EP:11			30%	3.15%	1.56%	1.58%	1.50%	1.54%	1.53%	1.52%	1.52%
EP:12	35%	70%	75%	18.38%	18.38%	18.38%	18.16%	6.86%	6.86%	3.67%	0.00%
EP:13			25%	6.13%	6.13%	6.13%	5.72%	4.90%	4.49%	2.04%	0.00%
EP:14		30%	40%	4.20%	4.20%	4.20%	4.16%	4.13%	3.96%	3.16%	0.00%
EP:15			60%	6.30%	0.00%	0.00%	0.00%	2.83%	2.83%	6.30%	6.30%
EP:16	35%	30%	35%	3.68%	0.00%	0.00%	1.00%	1.67%	1.67%	3.68%	2.67%
EP:17			15%	1.58%	0.53%	0.53%	1.05%	1.58%	1.58%	0.00%	0.00%
EP:18			50%	5.25%	0.00%	0.24%	0.11%	0.37%	1.00%	2.07%	5.25%
EP:19		20%	33%	2.33%	1.68%	1.83%	1.73%	1.72%	1.96%	2.00%	1.97%
EP:20			33%	2.33%	1.54%	1.56%	1.49%	1.71%	1.76%	1.74%	1.74%
EP:21			33%	2.33%	1.22%	1.19%	1.16%	1.49%	1.43%	1.33%	1.28%
EP:22		15%	100%	5.25%	0.03%	1.52%	0.03%	0.00%	0.49%	5.25%	5.25%
EP:23		35%	100%	12.25%	0.00%	0.00%	4.08%	8.17%	8.17%	12.25%	12.25%
Overall Weight/Score				**100.00%**	49.12%	54.27%	52.83%	49.92%	54.49%	65.38%	58.14%
Overall Rank					=7	=4	=5	=6	=3	=1	=2

From table 9, it is evident that the 2-wheeler delivery is ranked the highest while the coach bus is ranked the least in SSA. This can be attributed to affordability, minimal fuel consumption, underlying social benefits, government preference and support of the 2 Wheelers. Figure 11 illustrates the vehicle segment prioritization in SSA.

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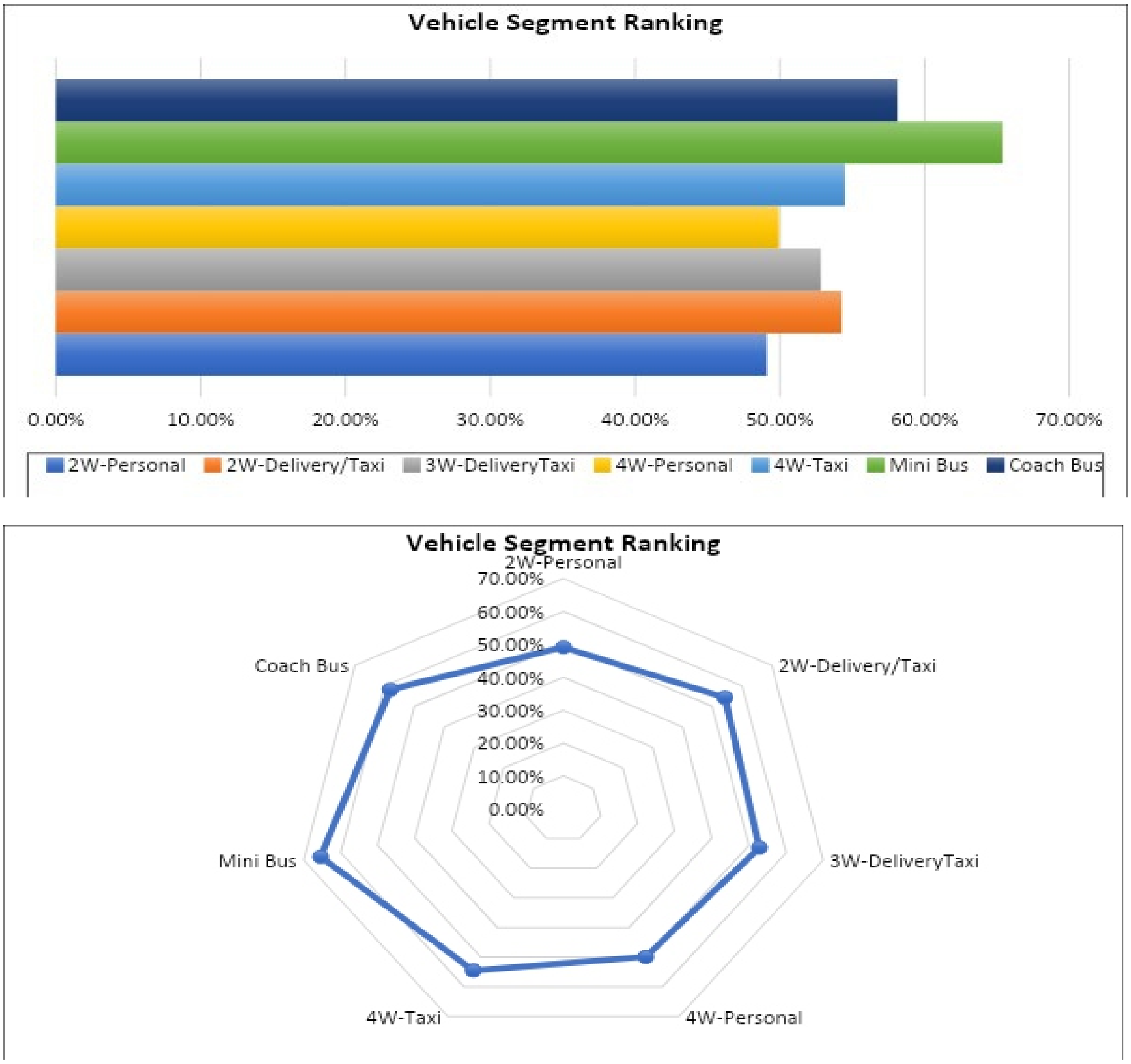


Figure 11: Vehicle segment weighted sum ranking

Based on Figure 11, the top three vehicle segments that should receive priority for 100% electric vehicle adoption in SSA are minibuses, coach buses, and 4-wheeler taxis. Minibuses and coach buses are ranked first and second, respectively, due to their higher aggregation of vehicle trip length, fuel consumption benefits, potential for cost savings in operation and maintenance, and potential for reducing air and greenhouse gas emissions. Therefore, when considering vehicle segment prioritization, emphasis in SSA should be placed on value addition stemming from social and economic benefits. These findings are consistent with the electric mobility studies conducted by UNEP on the African continent [86, 87].

Regarding the retrofitting of existing internal combustion engine vehicle fleets, it is crucial to also consider 2-wheeler and 4-wheeler personal vehicles, which are prevalent throughout SSA. Therefore, all vehicle segments except for 2-wheeler and 4-wheeler personal vehicles should be included in the barrier analysis to address the needs of the entire SSA region.

4.1.5. Sensitivity Analysis

To ensure the reliability of the vehicle segment prioritization methodology, a sensitivity analysis was performed on the key driving criteria for levels 1, 2, and 3 separately. Level 1 involved adjusting costs by +/-5%, while level 2 involved adjusting economic, social, and local pollution reduction benefits by +/-5%. For level 3, the willingness of the government to provide fiscal incentives was also adjusted by +/-5%. Table 10 provides a summary of the rankings for several sensitivity scenarios, including the base case, to determine the variations in vehicle segment prioritization.

Table 10: Vehicle segment prioritization for various sensitivity cases

No.	Sensitivity Scenario	**Criteria Level**	**Vehicle Segment Ranking between 1 and 7**						
			2W-Personal	2W-Delivery/Taxi	3W-Delivery/Taxi	4W-Personal	4W-Taxi	Mini Bus	Coach Bus
1	Base		**7**	**5**	**4**	**6**	**3**	**1**	**2**
2	Costs +5%	Level1	7	4	5	6	3	1	2
3	Costs -5%	Level1	7	4	5	6	3	1	2
4	Economic +5%	Level2	7	4	5	6	3	1	2
5	Economic -5%	Level2	7	3	6	5	4	1	2
6	Social +5%	Level2	7	3	5	6	4	1	2
7	Social -5%	Level2	7	4	5	6	3	1	2
8	Pollution +5%	Level2	7	3	5	6	4	1	2
9	Pollution -5%	Level2	7	4	5	6	3	1	2
10	Fiscal incentives +5%	Level3	7	4	5	6	3	1	2
11	Fiscal incentives -5%	Level3	7	4	5	6	3	1	2

Table 10 and Figure 12 demonstrate that the rankings for the first (minibus), second (coach bus), and last (2W-personal) vehicle segments remained consistent for all 10 sensitivity scenarios, indicating the robustness of the EV prioritization approach. However, the vehicle segments with varying ranks (between 2 and 7) include the 2W-delivery/taxi, 3W-delivery/taxi, and 4W-taxi. For instance, based on the analysis of the 10 sensitivity scenarios, the 2W-delivery/taxi had a rank of 3 and 4, 30% and 70% of the time, respectively. The 3W-delivery/taxi had a rank of 6 and 5, 90% and 10% of the time, respectively, while the 4W-taxi had a rank of 3 and 4 distributed in a 7:3 ratio.

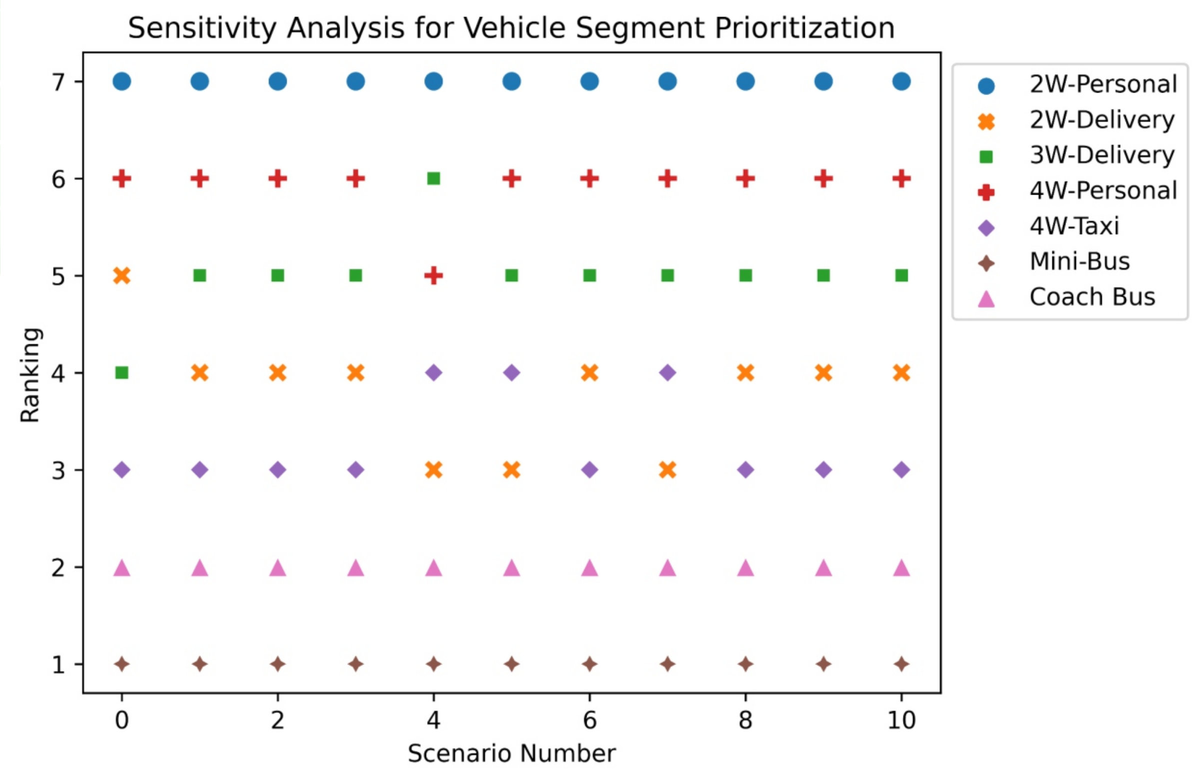


Figure 12: Vehicle segment prioritization sensitivity analysis rank distribution

4.2 Barrier Analysis Framework

The barrier analysis was carried out using the AHP method. Analytic Hierarchy Process (AHP) is one of the Multi-Criteria decision-making methods that was originally developed by Prof. Thomas L. Saaty. In general, it is a method to derive ratio scales from paired comparisons using the table of Saaty given below:

Table 11: Table of Saaty

Value	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Can be used to express intermediate values

The inputs in this case were derived from the opinions of two members of the team that were analyzed with the result being averaged to get the final score. The figure below shows the results of the exercise:

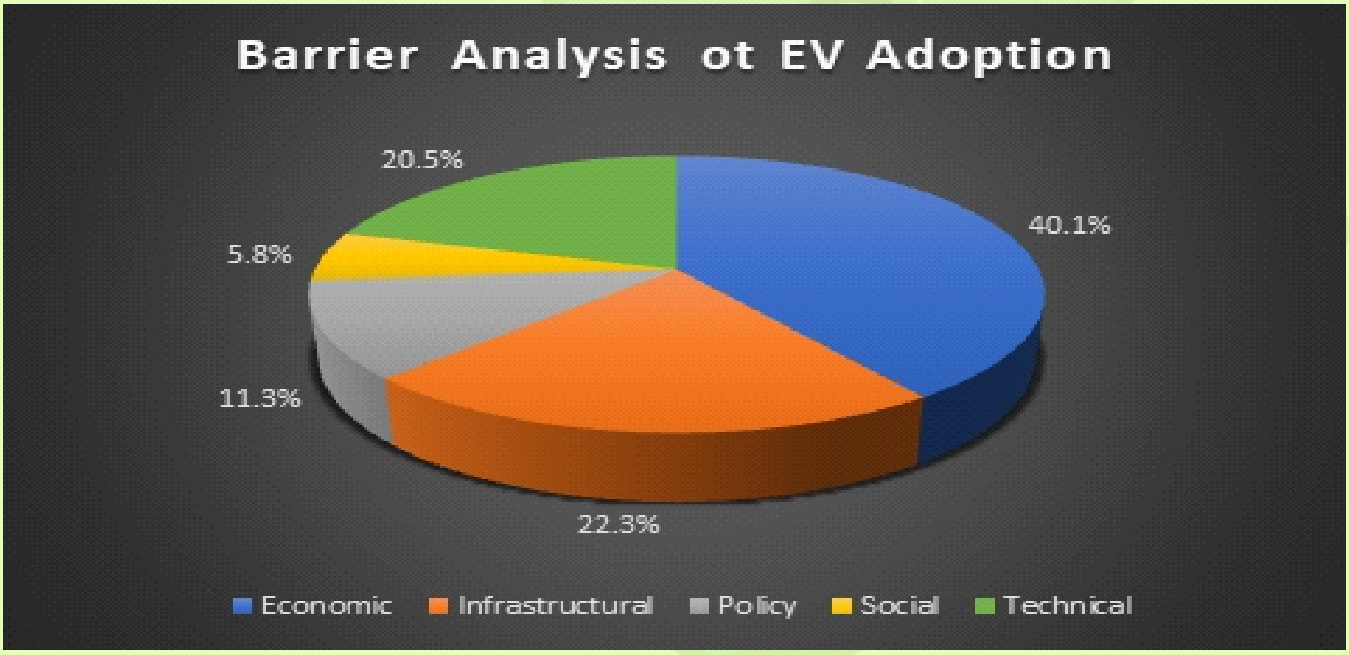


Figure 13. Barrier analysis for EV adoption

4.2 Barrier Analysis Framework - Cont.

Overall, the analysis proved that the economic barriers dominated with almost 40% score followed by Infrastructural with a score of 22.3%, and technical on third with 20.5% as shown in the pie chart above. This is consistent with the literature review which states that the capital cost of an EV itself, which is still more expensive than most fossil-fuelled private cars, is the first barrier to adoption. This concern does not relate to the cost of fuel or electricity. This makes buying an EV privately prohibitively expensive, especially in places like Nigeria, where 40.1% of the population still lives in poverty [89]. The same is true of Rwanda, Uganda, and SSA as a whole.

Policy and Social were the least barriers according to the study with a score of 11.3% and 5.8% respectively. The scores reinforce the idea in the literature that the social acceptance element takes into account the societal changes that the innovation brings about, such as in terms of billing behavior and travel habits. With conventional automobiles, customers are accustomed to traveling a long distance or for several days without refueling. The electric mobility revolution, however, means that they likely need to charge their cars every day at home or for a certain driving distance. Regarding policy, the e-mobility revolution in Africa requires policymakers to implement it. For Africa to effectively participate in global affairs, it must have legal criteria (such as local content requirements) and value chains in the industry of e-mobility. Therefore, it is necessary to promote investment in value chains in the continent's automobile industry to ensure that Africa plays a significant role in this industry going forward. The figure below further breakdown how the sub-criteria of each section performed:

4.2 Barrier Analysis Framework - Cont.

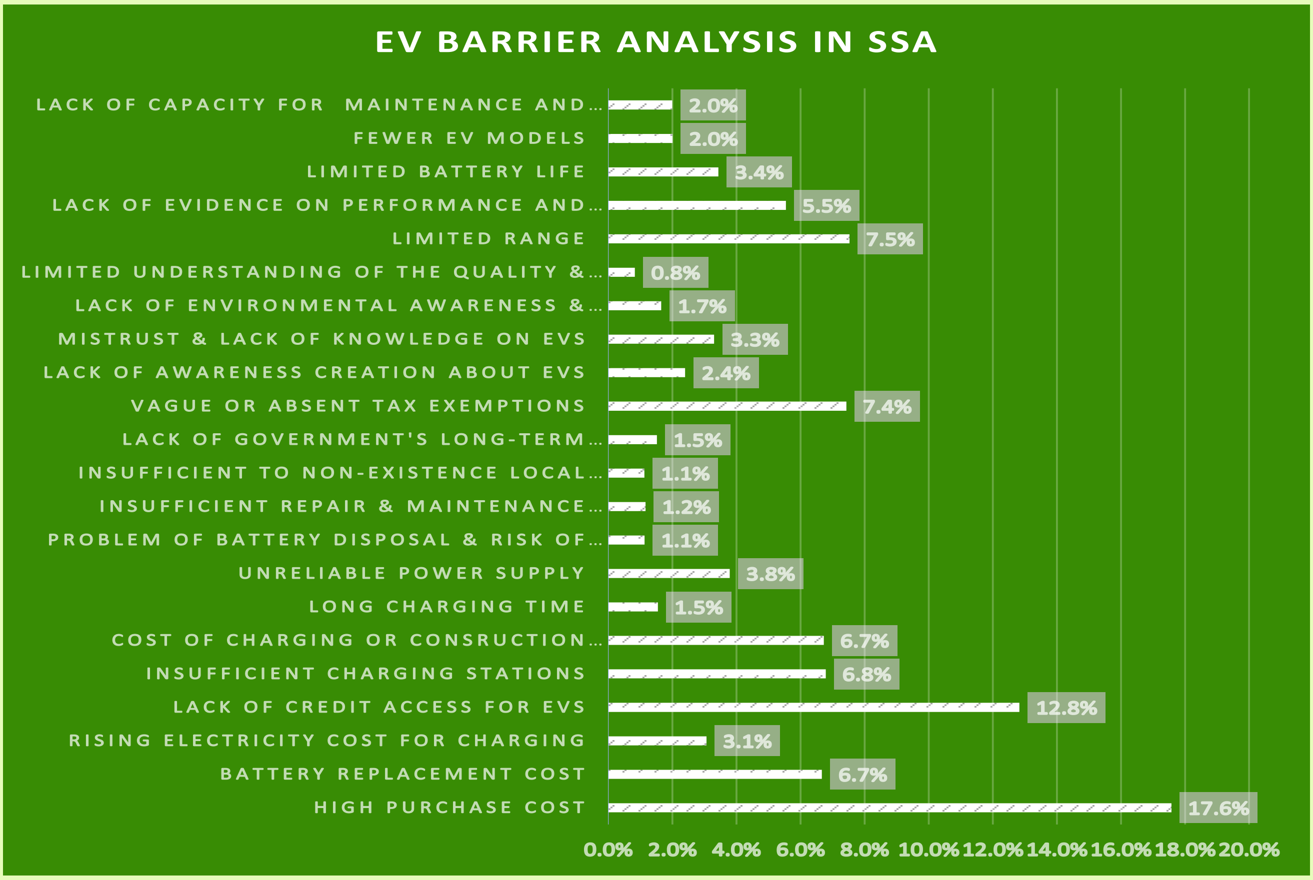


Figure 14. Barrier percentage weight distribution

Figure 14 shows that economic barriers are at the top starting with the High purchase cost of EVs being the number one (with a score of 17.6%) barrier regarding the adoption of EVs in SSA. The second barrier is the lack of credit access for EVs in SSA with a score of 12.8%. If we add the top 5 barriers: limited range (7.5%), the lack of tax exemptions on EV purchases with a score of 7.4% (with a ranking of 4), and insufficient charging systems (score of 6.8% and rank 5)- it means that if Governments can solve these top 5 barriers, they would have solved over half (52%) of the challenges in EV adoption regarding SSA context.

EV manufacturers also need to put extra effort into debunking some of the negative myths surrounding EVs. The figure above shows that the limited range with a score of 7.5%, lack of evidence in performance with a score of 5.5%, and limited battery life with a score of 3.4% also need attention if inroads in EV adoption are to be made. The study shows that it's necessary to develop context-appropriate technologies and the economic models that go along with them, whether it is for brand-new EVs or retrofit options like battery swaps, plug-in charging with collocated PV, or onboard PV.

The study also shows that there is a challenge regarding the charging of EVs in SSA. The lack of charging infrastructure and the cost of infrastructure contributed to a total of approximately 14% of the barriers. Grid reliability at 3.8% is another factor that needs to be solved. This is also reflected in literature which states that even in metropolitan areas, the electrification rate in SSA is far from complete. Even when there is electricity, access is not always guaranteed, and the electricity is neither consistent nor reasonably priced.

This obstacle highlights the necessity for an evaluation of the transmission losses, reliability, accessibility, and availability of electricity that have plagued the continent's energy supply before EV adoption [89]. In addition to the fact that 47% of Rwanda's population lacks access to electricity, the grid is unstable and there are frequent power outages [45]. Barely 6% of Kenya's electricity is used by families [48].The high costs of electricity were also identified as a barrier to electric vehicle diffusion in Johannesburg (and Cape Town) [52].

4.3 Policy Road Map

The barrier analysis conducted in this research showed that the economic barriers topped the list followed by infrastructural, technical, policy and lastly social. There is need to create an enabling environment spearheaded by the policy makers in the SSA region so as to accelerate the uptake of EVs. The list below show potential enabling policies or measures that can be adopted for implementation in SSA:

Table 12: Proposed policy enablers

Barrier Category	Suggested enabling measure
Economic	**Tax waivers** - Currently, majority of EV are imported hence import tax waivers - on VAT, excise taxes, and customs duties - that encourage importation of clean vehicles can be introduced and the net effect will be a reduction in upfront costs. These should continue to target SKD and CKD (semi- and completely-knocked down) vehicles to encourage local assembly and manufacturing.
	Reduced bank loan interests - Availability of fair and affordable loans to purchase EVs should be prioritised so as to improve the barrier lack of credit access which had the second highest score. The government could subsidise the interest. Special funds could be designed for electric vehicle financing for consumers and businesses to make EVs more accessible for low-income people.
	Funding for e-mobility startups - Currently, most e-mobility startups in Africa have been funded by a combination of equity investments from Western venture capital firms, small grants, and personal funds. Being a capital-intensive business, the demands are high, and there is a need for a huge wave of investment in these startups across the continent. Furthermore, for African countries to benefit from the huge growth in these companies, governments and pension funds should begin investing.
	Cut-off dates for selling ICE vehicles. Governments should set cut-off dates beyond which ICE vehicles can no longer be sold - such as 2040 - to create a strong impetus for the industry.

4.3 Policy Road Map - Cont.

Infrastructural	**EV Charging Infrastructure subsidies and incentives** - stakeholders should be encouraged to construct charging infrastructure by providing incentives and subsidies. Lack of charging infrastructure scored 6.8% in this research hence it needs to be addressed. Charge points and battery swap stations should be readily accessible with areas like office parking lots, street parking, fuelling stations.
	Cheaper energy tariff for EVs - implementing a tariff that encourages charging of EVs will go a long way in accelerating them in SSA. Systems like Time of Use tariff will encourage people to charge the EVs using a cheaper tariff when demand is low. Use of PV especially in private houses can also be beneficial if there is need to charge during the day. Governments should assess current tariffs to ensure that EV users are not paying more per kWh than residential rates.
	Increasing Electrical Accessibility - lack of reliable power supply scored 4% in this research. Creating an enabling environment for EV adoption in SSA will have to include greening, expanding, and reinforcing the grid so that integration of EVs for charging becomes easier.
Social and Policy	**Clearly articulated Government policy and roadmap on EVs** - Governments in SSA should clearly present their position and plan in terms of EV adoption. They should be clear targets supporting policies that encourage EV adoption. Governments should lead by example by adopting EVs in their fleets.
	EV Awareness - An EV awareness campaign should be considered in SSA countries. This campaign should target both the industry and the general public. This paper showed that there is a lack of trust and misinformation surrounding EVs. Fitting with the technology of the day, print and electronic media should also be utilised to articulate and debunk all the grey areas regarding using EVs. Social media applications like WhatsApp and TikTok should be utilized to create publicly-accessible information.
Technical	Technical barriers like limited range, lack of evidence on performance and reliability and limited battery capacity all had a combined score of 16.4%. SSA countries should prioritise EVs that provide public services, such as minibuses, motorcycles, and tuktuks. Coupled by increasing accessibility to battery swapping and fast chargers, this will solve the range challenge. Research on EV performance should be encouraged so that there can be evidence showing the technology status on maturity, performance, and reliability.

4.4. Modeling Costs, Energy Use and Carbon Emissions

This section presents results for modeling the various vehicle propulsion types in four SSA countries namely Zambia, Zimbabwe, Rwanda and Nigeria. The key modeling attributes for the 'do-nothing' also called the 'base' scenario are presented in table 13 below:

Table 13: High-level modeling inputs for the various scenarios

AFLEET TOOL INPUTS				
Input	**Zimbabwe**	**Zambia**	**Nigeria**	**Rwanda**
Type of car (gasoline)	Toyota	Toyota	Toyota	Toyota
Type of car (diesel)	Toyota	Toyota	Toyota	Toyota
Annual Vehicle mileage (miles)	12627	12627	12627	12627
Car economy (miles per gallon) gasoline	30.9	30.9	30.9	30.9
Car economy (miles per gallon) diesel	37.1	37.1	37.1	37.1
Car economy (miles per gallon) EV	106.2	106.2	106.2	106.2
Car purchase price (usd) EV	US$45,678.00	US$50,400.00	US$62,679.56	US$23,351.24
Car purchase price (usd) Gasoline	US$33,508.00	US$38,200.00	US$22,900.00	US$20,731.23
Car purchase price (usd) Diesel	US$39,245.00	US$45,200.00	US$24,470.00	US$21,070.15
Gasoline Price (usd/gallon)	US$5.75	US$5.16	US$1.70	US$5.43
Diesel Price (usd/gallon)	US$6.59	US$5.54	US$6.27	US$5.49
Electricity (usd/kwh)	US$0.10	US$0.05	US$0.05	US$0.25
Years of planned car ownership	15	15	15	15
Loan term (years)	5	5	4	4
Interest Rate (%)	29%	25%	5%	8%
Percent Down Payment (%)	20%	20%	20%	20%
Discount Factor (%)	1.24%	1.24%	1.24%	1.24%
Fossil grid contribution (%)	21%	13%	77%	51%
Renewables grid contribution (%)	79%	87%	23%	49%

4.4.1. Do Nothing or Current Policy Scenario

4.4.1.1. Simple Payback

Figure 15 displays the payback outcomes for a 5-light vehicle in four distinct countries located in Sub-Saharan Africa (SSA), based on the type of propulsion fuel used, namely diesel, gasoline HEV, gasoline PHEV, EV, and G.H2 FCV. Gasoline is considered the benchmark for all other vehicle types and, as a result, is not included in the analysis. The results indicate that vehicles such as diesel and hydrogen fuel cell demonstrated "no payback" due to negative annual operating savings in the model outcomes.

For EVs, the average payback period across the four countries is 10.9 years, with Nigeria exhibiting the highest simple payback period of 33 years. Once again, Nigeria's simple payback period is the highest among the four countries for gasoline PHEVs, with a simple payback of 49 years, while the average across all countries is 18.3 years. As for gasoline HEVs, the average payback period is 15.1 years, with Nigeria having the longest simple payback period of 24 years. Although some savings are feasible with these modes, the payback periods are relatively long, making it challenging to incentivize consumers.

Rwanda has the lowest simple payback period due to its policy of encouraging EV manufacturing in the country, thus reducing its price [87]. Nigeria tops all the sections under review, which is consistent with literature indicating that the current cost of EVs in Nigeria is excessively high and would need to decrease by 40% to become cost-competitive [88].

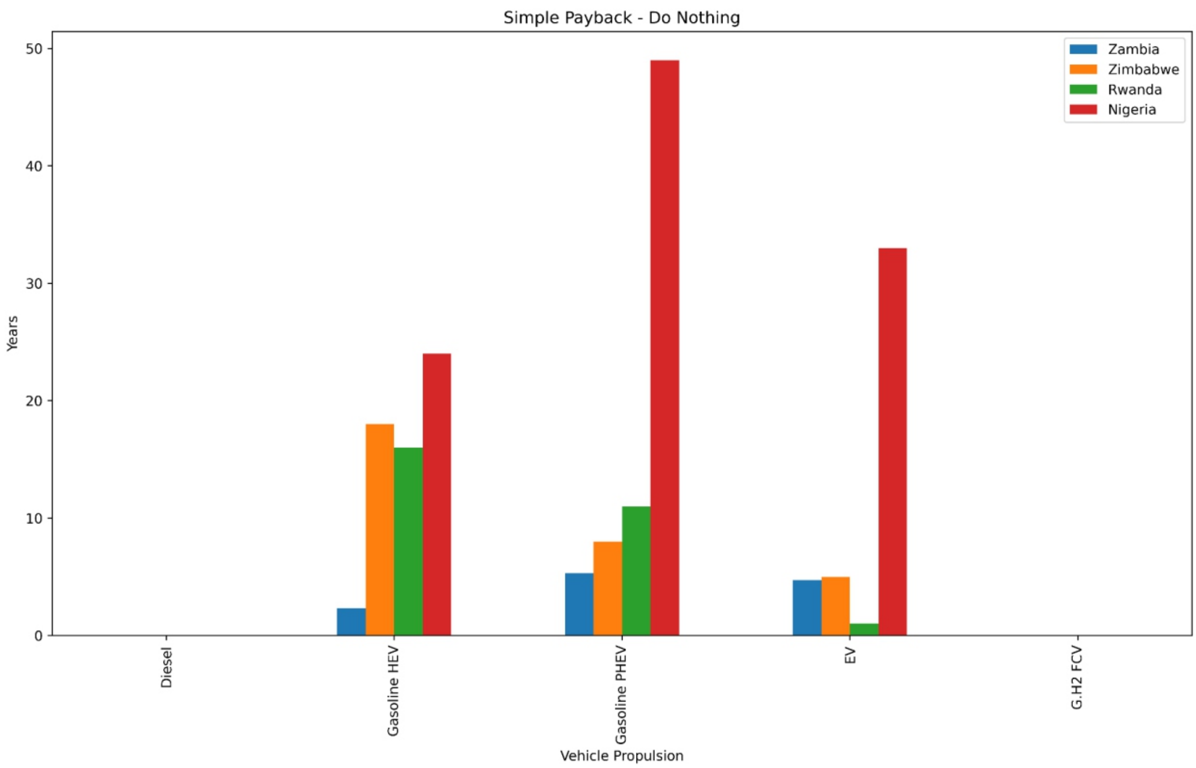


Figure 15: Simple payback for the do-nothing scenario

4.4.1.2. Total Cost of Ownership

Figure 16 illustrates the total cost of ownership (TCO) for the various vehicle modes being evaluated across the four countries. When considering factors such as financing, depreciation, fuel, maintenance and repair, insurance, license, and registration, the EV has the lowest TCO across all countries, with the exception of Nigeria. This indicates that the EV is the most cost-effective option overall, except for in Nigeria.

However, the low TCO for gasoline cars in Nigeria is due to the comparatively low cost of fuel and financing when compared to the other countries. On the other hand, the diesel vehicle mode has the highest TCO cost, primarily due to its high maintenance and repair expenses when compared to the other vehicle modes.

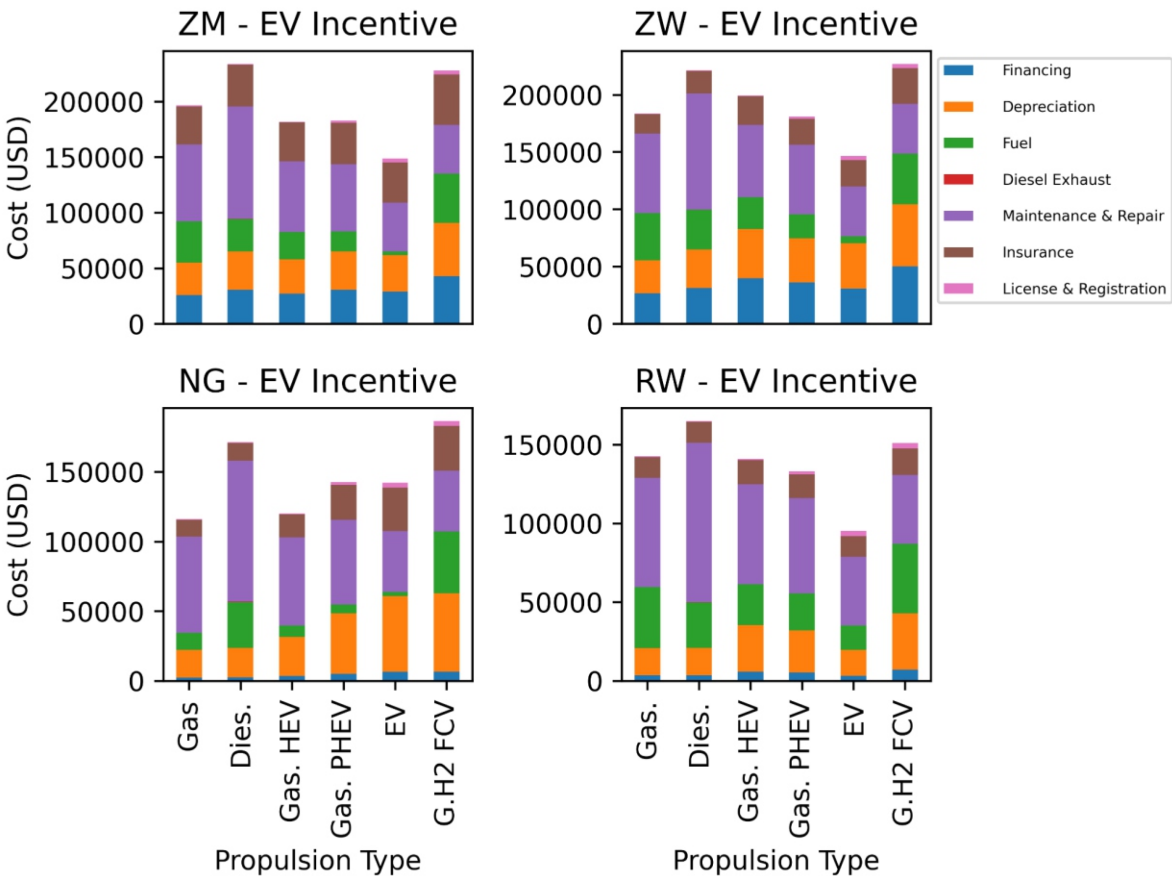


Figure 16: TCO for the do-nothing scenario

4.4.1.3. Greenhouse Gases (GHGs)

Figure 17 depicts the lifetime well-to-wheels (WTW) greenhouse gas (GHG) emissions for the six vehicle modes across the four SSA countries. In general, the trend follows the fuel economy of different fuel modes. The analysis reveals that all alternative fuels provide better WTW performance than conventional oil-based gasoline/diesel when used in internal combustion engines (ICEs), which is consistent with the literature [89]. Evs exhibit the lowest emissions, with the emission rate based on the amount of renewable energy mix in the grid. In general, the hybridization of conventional ICEs decreases GHG emissions by up to 33% for HEVs and up to 50% for plug-in HEVs (in Zambia).

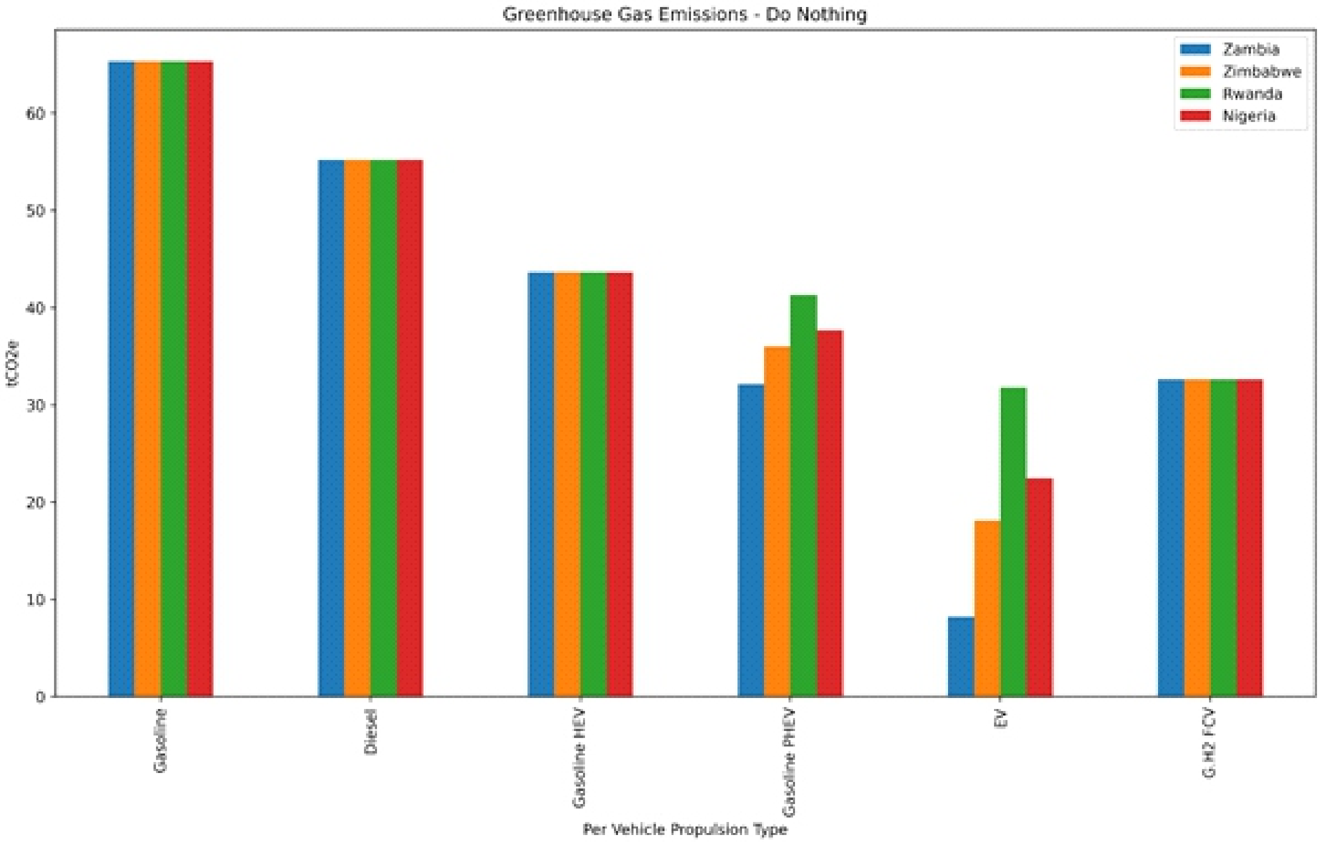


Figure 17: GHGs for the do-nothing scenario

4.4.1.4. Air Pollutants

Figure 18 presents the air pollutants emitted bythe different vehicle modes being evaluated across the four SSA countries. The analysis reveals a similar trend across all four countries, where oil-based ICEs have the highest concentration of pollution, followed by hybridized ICEs, with EVs and G.H2 FCVs exhibiting the lowest levels of pollution.

As shown in the figure, carbon dioxide emissions over the lifetime of the vehicle are at the top of each bar for all vehicles with oil-based engines. The percentage with respect to the gasoline and diesel cases is also at the top when compared to HEV and PHEV bars. This is consistent with the literature review, which states that pollution and global warming can be reduced by using HEVs as cleaner alternatives to traditional ICEVs [91].

Based on the graphs below, it can be concluded that EVs and G.H2 FCVs are zero-emitting vehicles when compared to ICE and hybrid ICE. The difference is based on the type of fuel used. However, for EVs, it is important to note the source of electricity, as the energy mix is critical when analyzing the pollution contribution from these vehicles.

4.4. Modeling Costs, Energy Use and Carbon Emissions - Cont.

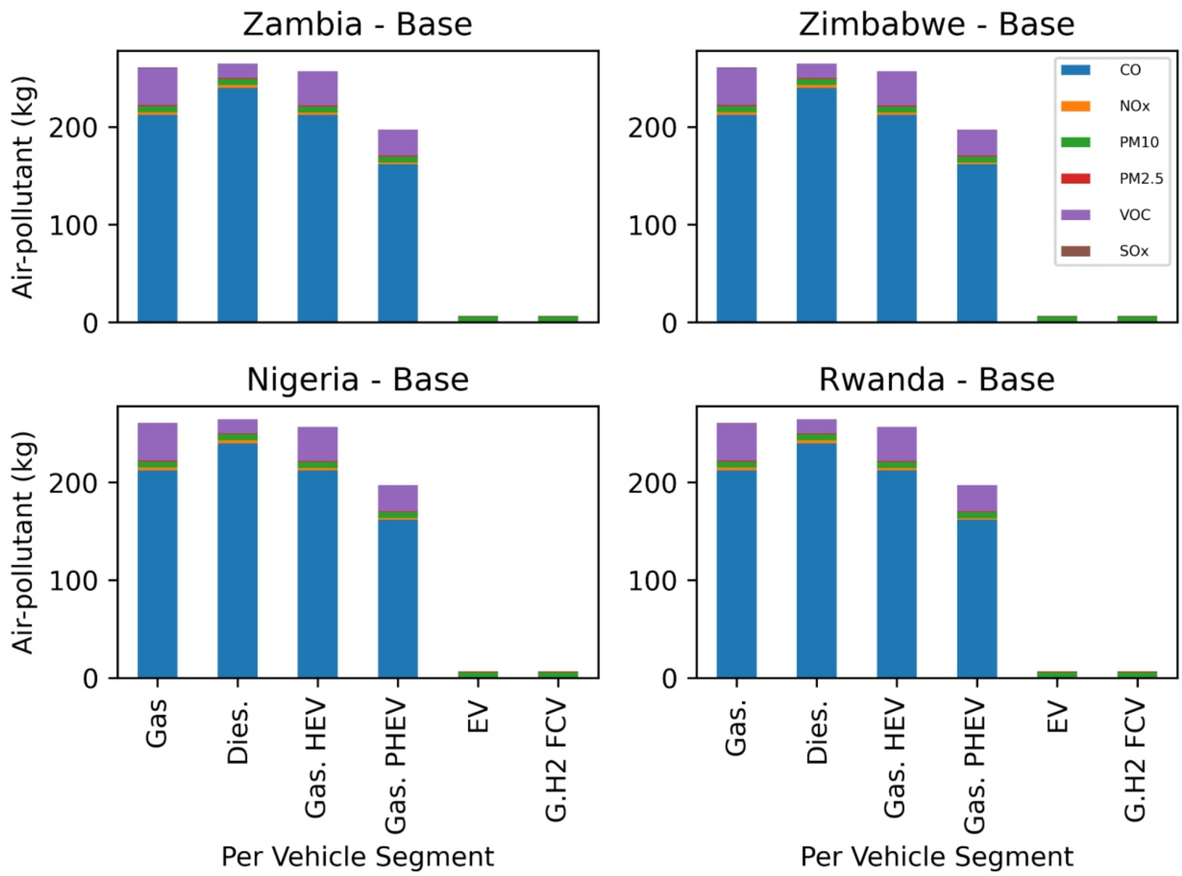


Figure 18: Air pollutants for the do-nothing scenario

4.4.1.5.Minibus Carbon Footprint

In Figure 19, the GHG footprint for operating a petrol and diesel minibus in the 4 countries in SSA under review is shown. The results are consistent with the literature review [91], where the GHG footprint for diesel is slightly better than that of gasoline. Gasoline constituted 53% of the total, while diesel constituted 47% in terms of percentage. This can be attributed to better fuel conversion efficiency, which leads to lower volumetric fuel consumption when compared to gasoline [91, 92].

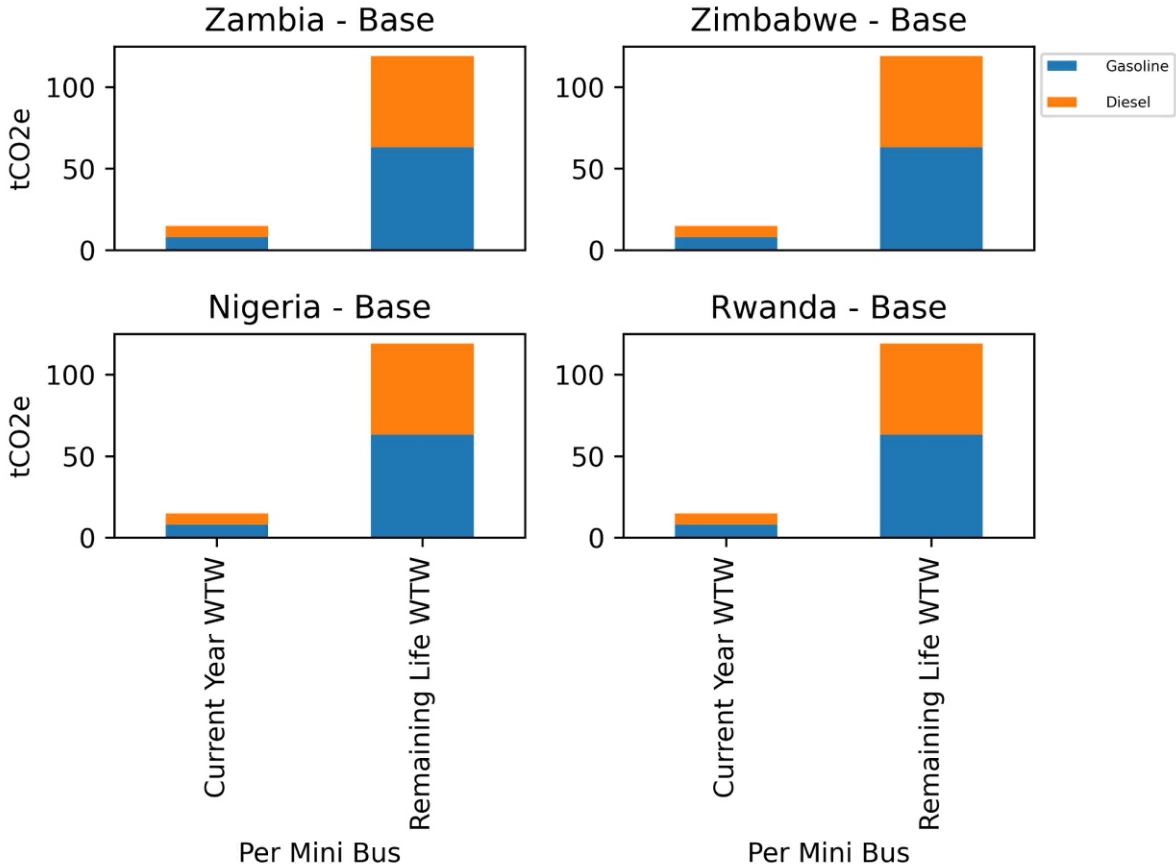


Figure 19: Minibus carbon footprint for the do-nothing scenario

4.4.2. Policy Road Map Application & Sensitivity Analysis

4.4.2.1. Tax Incentives

The importance of government policies in promoting the usage of zero emission vehicles (EVs) is emphasized in national policy documents across SSA countries. Therefore, policymakers need to understand the cost-effectiveness of these policies and the environmental benefits of EVs. The barrier analysis conducted in section 4.2 and the policy roadmap in section 4.3 demonstrated that EV purchases would benefit from government policies that encourage their adoption. As such, a hypothesis is proposed to reduce the capital cost of EVs by 15%, and Figure 20 below shows the effect on payback. Overall, implementing such a policy would reduce the average payback of EVs among the 4 countries by approximately 34%. This reduction can also be observed in TCO, as shown in Figure 21 below. The analysis demonstrates that implementing such a policy would reduce the TCO of EVs by an average of 11% across the 4 countries.

4.4. Modeling Costs, Energy Use and Carbon Emissions - Cont.

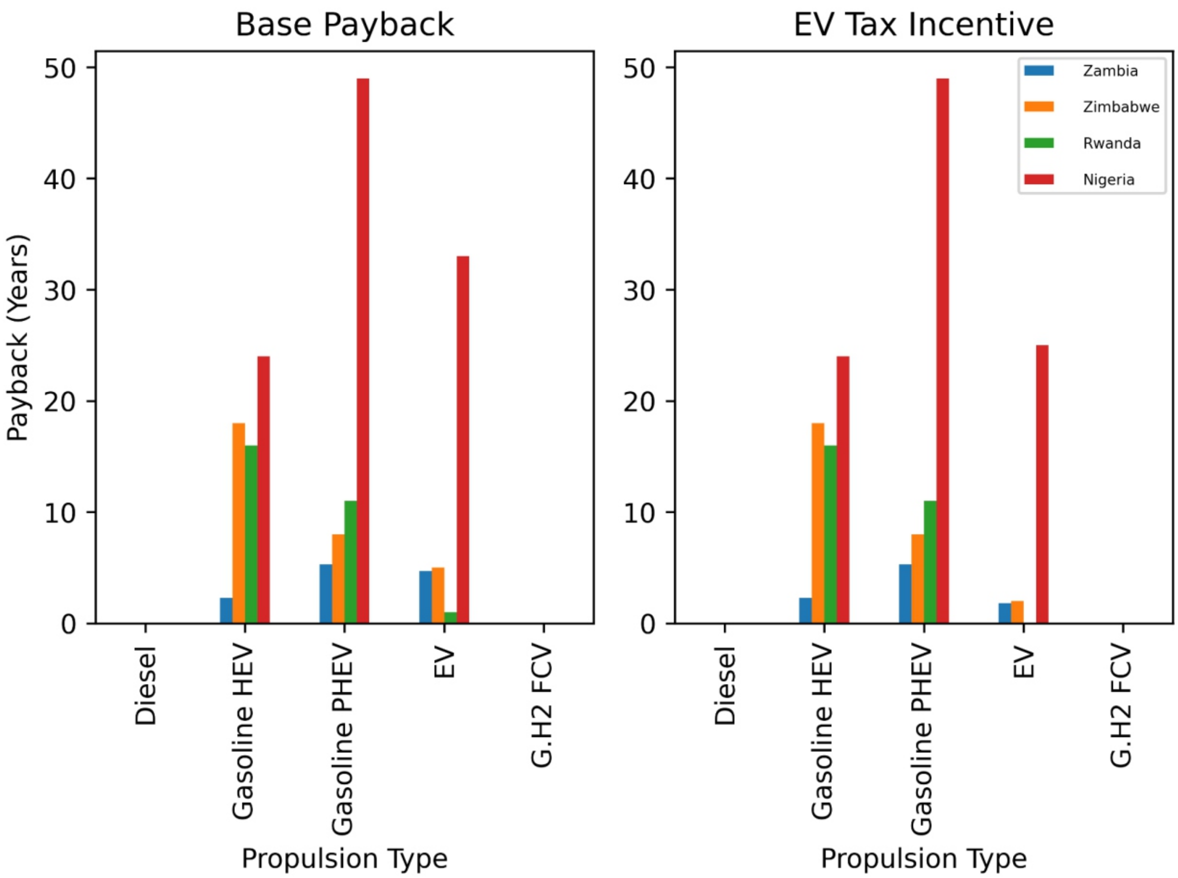
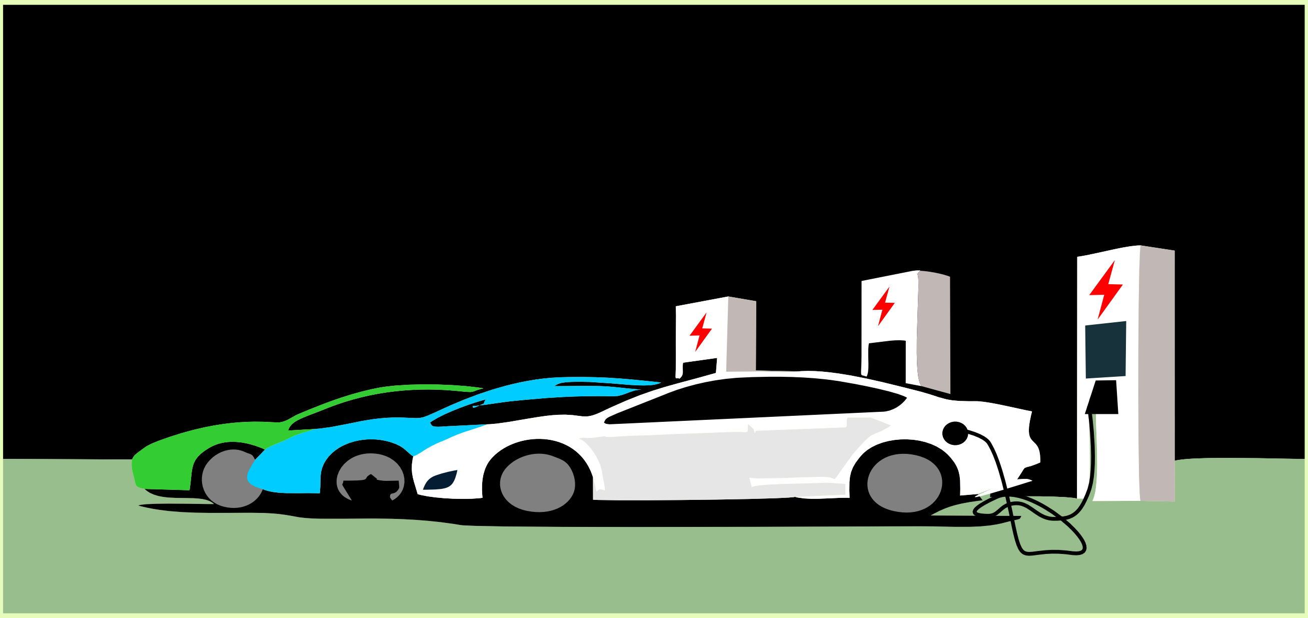


Figure 20: Sensitivity on simple payback



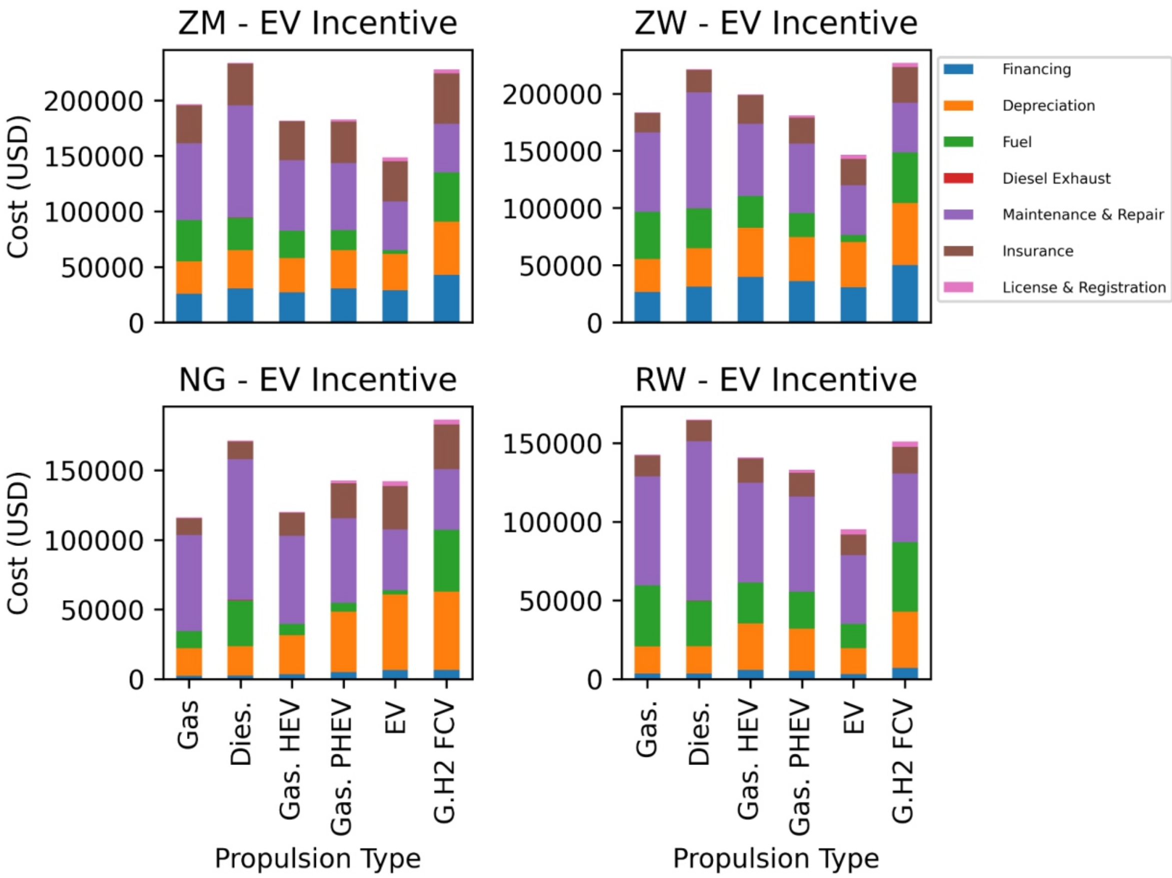


Figure 21: Sensitivity on TCO

4.4.2.2. Reduced Interest Rates

As presented in section 4.2, limited access to credit was identified as the second most significant barrier to EV adoption. To address this, reducing interest rates on credit lines could improve access and promote EV adoption. To test this hypothesis, the effect of reducing bank interest rates by 10% in all four countries was analyzed. The results, as shown in Figure 22 below, indicate an average 8% reduction in TCO for EVs across the four countries, making EVs more affordable for potential buyers.

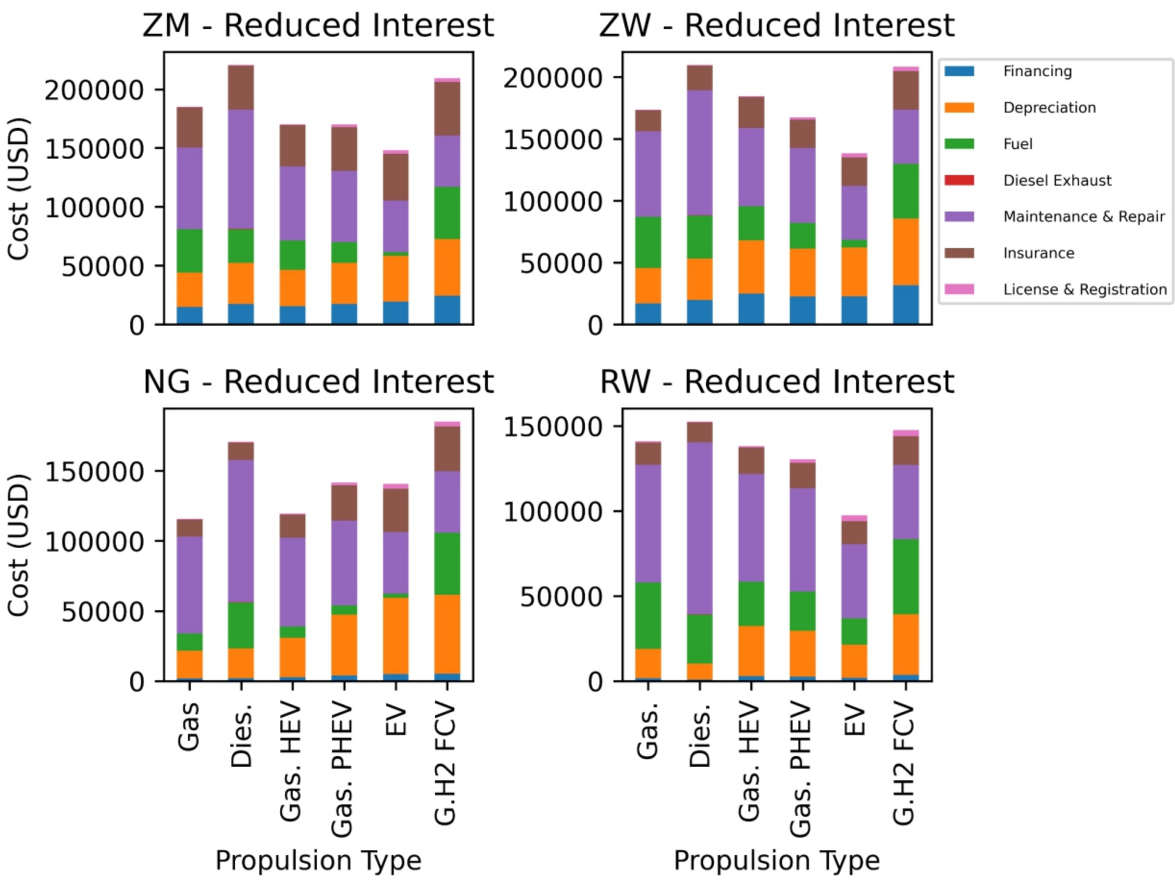


Figure 22: Reduced internet rates

4.4.2.3. Greening the Grid

An EV is as green as the charging station charging it which is only as green as the grid supplying the electricity. There is an opportunity to fully utilise the zero emission of the EV by introducing renewables into the grid. This hypothesis was tested by running the Afleet tool with 100% renewable mix. Figure 23 below shows that the emission in all the for countries for EV became zero and there was also reduction in emissions in the PHEV. The results concur with literature which states that EVs have the capability to become greener as the utility portfolio becomes greener [93].

4.4. Modeling Costs, Energy Use and Carbon Emissions - Cont.

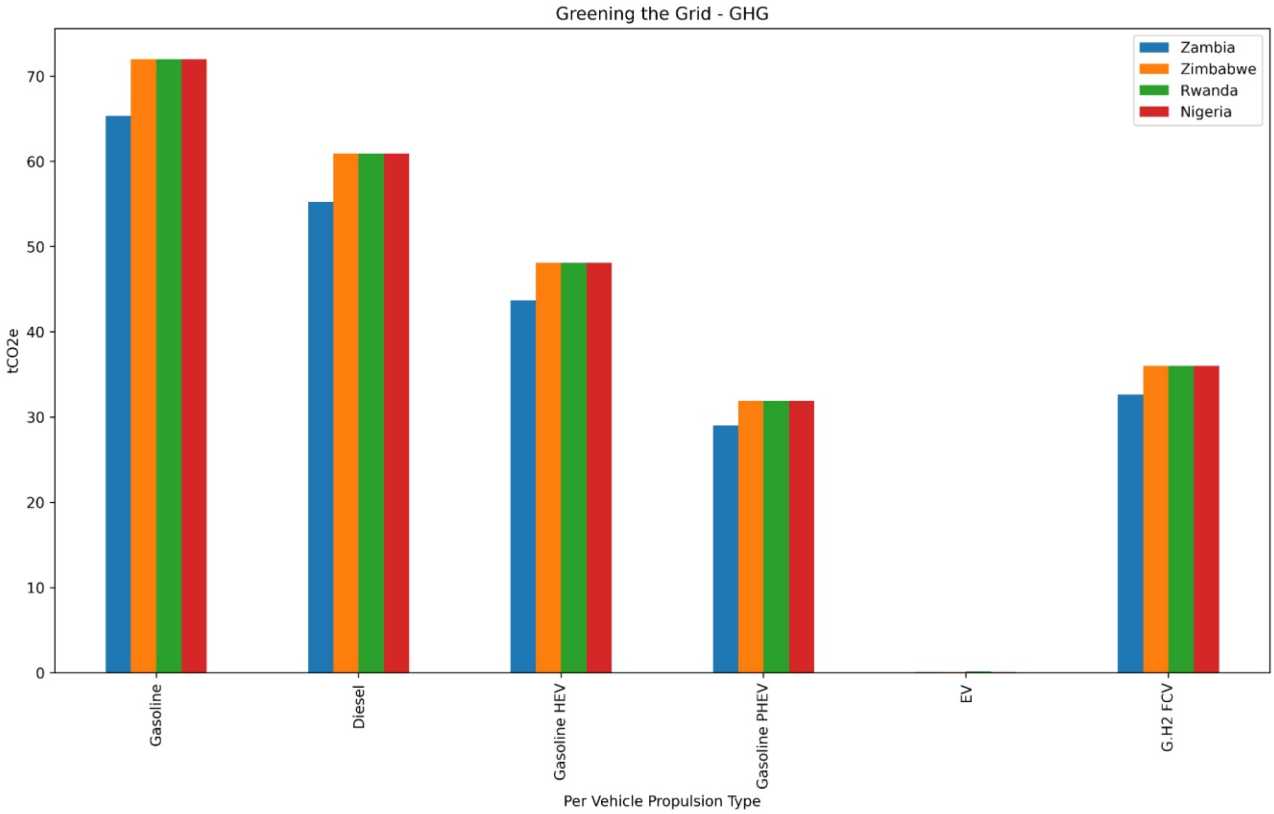
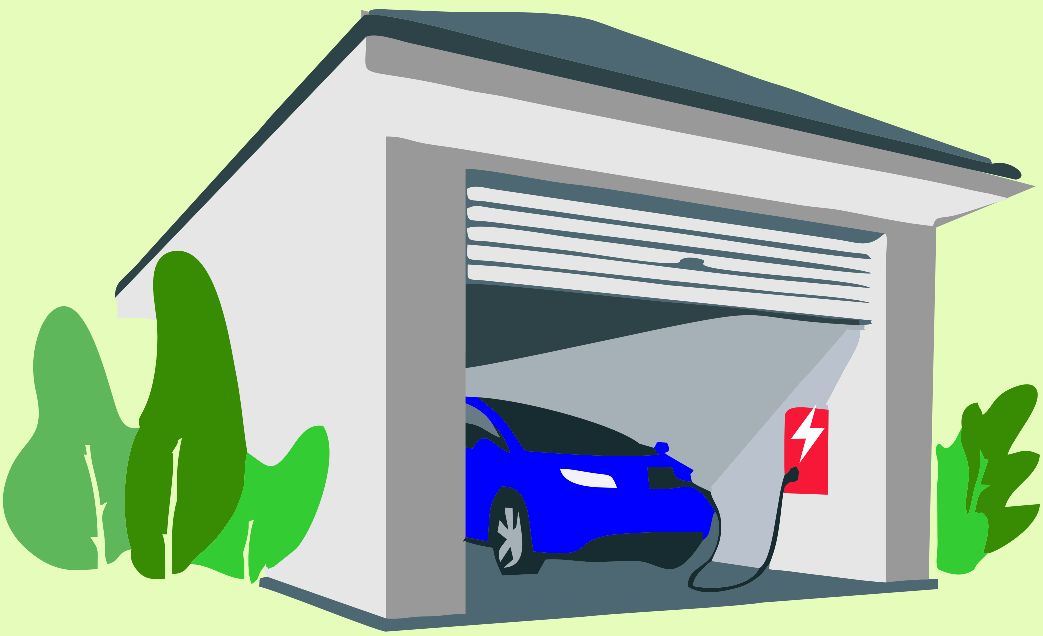


Figure 23.. Greening the Grid



5. Conclusions and Recommendations

This research aimed to explore ways to fast-track electric mobility adoption in Sub-Saharan Africa (SSA), focusing on Zambia, Zimbabwe, Rwanda, and Nigeria. The study employed a multi-criteria decision-making approach to prioritize vehicle segments in the region based on 23 assessment criteria. The identified barriers to EV adoption were then analyzed using the same approach. The study found that minibuses, coach buses, and 4 wheeler taxis should receive priority for 100% electric vehicle adoption in SSA. The analysis also proved that economic barriers dominated with almost 40% score followed by infrastructural with a score of 22.3% and technical barriers with 20.5% score. The study also established a policy roadmap for each country, benchmarked the initial cost of adopting electric mobility against traditional vehicles, evaluated potential greenhouse gas and air pollutant benefits of EVs in comparison to traditional vehicles, and identified limitations of the methodology.

The study acknowledges limitations to the methodology, such as diverse priorities among countries, heavy reliance on a literature review resulting in data based on assumptions, and subjective pairwise comparisons in the Analytic Hierarchy Process. To ensure the reliability of the vehicle segment prioritization methodology, a sensitivity analysis was performed on the key driving criteria for levels 1, 2, and 3 separately. To address the needs of the entire SSA region, all vehicle segments except for 2-wheeler and 4 wheeler personal vehicles should be included in the barrier analysis.

Based on the research findings, the study recommends that policymakers and stakeholders prioritize the deployment of electric minibuses, coach buses, and 4 wheeler taxis in SSA. Governments should address economic and infrastructural barriers to promote EV adoption, including reducing the initial cost of EVs and establishing charging infrastructure.

Stakeholders should also consider the potential social and environmental benefits of EVs and work towards addressing social acceptance barriers. Future research should focus on developing customized models for individual countries in SSA and addressing limitations in the methodology. Additionally, future studies should consider the potential of alternative fuels and sustainable transportation systems in SSA.

6. Acknowledgments

We would like to extend our sincere gratitude to the following individuals and organizations whose support and contributions have been pivotal in the completion of this research article, titled "Fast Tracking Electric Mobility in Sub-Saharan Africa: An analysis of vehicle segment prioritization, barriers to adoption, and policy roadmap development on GHG emissions."

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- Mr. Steven Mwiinga, Senior Manager Electricity at Energy Regulation Board (ERB) for his continued support to e-Mobility and engaging all stakeholders. Under his guidance, the first-ever gathering of stakeholders was convened to pave the way for e-Mobility in Zambia.
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