

ANALYSIS

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Comparative analysis of city-specific EV applications for passenger transport in Asia and Africa

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Abstract

Electric mobility is progressing at varied paces for different vehicle segments, and in many countries, significant barriers exist, which is reflected in the very low share of electricity in final energy consumption. The EU-funded SOLUTIONSplus project, which promotes sustainable urban transport through electric mobility, demonstrated e-three-wheelers in Dar es Salam and Kathmandu, remodelled Safa tempos in Kathmandu, e-moto taxis in Kigali, e-mopeds in Hanoi, and bus conversion in Kathmandu. These prototypes, developed, produced and/or assembled by local firms, were specifically designed to replace fossil fuel-powered two-wheelers, three-wheelers and buses, reflecting local conditions and aims. The assessment of demonstrations uses financial cost-benefit analysis (CBA) and key sustainability indicators based on local stakeholders' priorities. All demonstration vehicles turned out profitable in cases where they replaced an existing ICE vehicle. The upfront cost of electric vehicles is high. However, the total cost of operations of electric vehicles has shown that they are more profitable in the long run. and also have significant social, environmental and climate benefits. The CO₂ reduction is substantial for all EVs since they replace ICE vehicles, however, these can increase further if electricity grids can be decarbonised. Since EVs have no tailpipe emissions of (NO_x, PM) the reductions of local emissions are 100%; however, improvements in emission standards for ICE vehicles will reduce the advantage of EVs in future. EVs in themselves cannot lead to improvements in accessibility, affordability and travel time savings. However, when they are used to expand/complement public transport, they can improve accessibility (Dar es Salam) and deliver time-savings (Hanoi).

Keywords Electric mobility, Emerging economies, Impacts assessment

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Introduction

Addressing the rapid rise of fossil-fuel motorisation is crucial to limit transport-related greenhouse gas (GHG) emissions. In 2019, transport accounted for 23% of global energy-related CO₂ emissions [1], since vehicles are mostly powered by petroleum products (95.9% in 2020). The road sub-sector accounts for 70% of these emissions [2]. Worse, the transport sector's GHG emissions have grown faster than all other end-use sectors [1]. The need for mobility is expected to maintain its upward trajectory in the coming decades. Under its current ambition scenario, the International Transport Forum (ITF) projects a 79% increase in passenger demand by 2050 [3] and likewise, an increase in GHG emissions is expected.

To mitigate transport-related emissions, electric mobility is posed as one of the pathways to decarbonise urban mobility, alongside mode shift from individual vehicles to public transport and active mobility and demand-management policies [3]. The Intergovernmental Panel on Climate Change (IPCC) identifies transport electrification as one of the key mitigation options for land transport [1].

Electric mobility is progressing at varied paces for different vehicle segments. Electric two- and three-wheelers are the most electrified vehicle segment, and 13% of total sales in 2023 were electric vehicles, with most sales in China (84% of e-two-wheeler registrations) and India (425,000 e-three-wheelers sold) [4]. Electric buses have gained popularity since 2020, with almost 50,000 units sold globally in 2023 [4]. Historically, China has the largest stock of over 635,000 buses; however, China is increasingly exporting buses to Latin America, North America and Europe [4].

Despite the growing recognition of the necessity to move away from fossil-fuel engines, the transition is still challenging in most countries. With a share of electricity in total final energy consumption of only 1.4% in 2020, the transport sector lags well behind other sectors [2]. There are several barriers to the adoption of electric vehicles, including financial, vehicle performance and infrastructure barriers [5]. The high purchase cost of EVs is a significant challenge, especially in low- and middle-income countries [6]. Yet, developments in the e-motorcycle commercial segment in sub-Saharan Africa, have also shown the capacity to develop innovative business models overcoming the financial barrier [7, 8]. In addition, EVs may be perceived as riskier or less efficient than conventional vehicles [9]. Another challenge is the lack of access to reliable electricity, particularly in sub-Saharan Africa [10]. In low- and middle-income countries, the atomised characteristics of paratransit with small-size and privately-owned minibuses may represent a further difficulty [11]. Lastly, the lack of adequate charging

infrastructure causes range anxiety and hinders EV adoption, particularly for electric two wheelers in Asia [5].

The SOLUTIONSplus project, funded by the European Union, seeks to facilitate a transformative shift towards sustainable urban mobility by promoting electric mobility. As part of this initiative, demonstration activities have been implemented to enhance public transportation connectivity in Africa and Asia. In Dar es Salam, Tanzania, e-three wheelers have been introduced, while e-moto taxis have been deployed in Kigali, Rwanda. Similarly, in Hanoi, Vietnam, e-mopeds and e-bikes have been piloted, and in Kathmandu, Nepal, Safa tempos (old e-3W) have been retrofitted, new electric three- and four-wheelers have been designed for passenger services, and a diesel bus has been converted to electric. All the prototypes have been designed and developed locally in certain instances, manufactured by local enterprises, aiming to substitute fossil fuel-powered vehicles. In all cases, the specific circumstances and objectives of the local context have been considered [12].

These actions aim to demonstrate the viability and benefits of electric vehicles (EVs) as a sustainable alternative to traditional fossil fuel-powered vehicles. This includes reducing greenhouse gas emissions, lowering air pollution, and decreasing reliance on imported fuels. The demonstration projects also aim to check the technological readiness and practicality of proposed electric mobility solutions in diverse environments and under various conditions prevalent in Africa and Asia. This article will provide the preliminary findings of the research, accentuating the financial assessment of the examined alternatives, while also checking for its effect on climate, environment and social impact indicators. This is done to assess the unique factors of significance to the local populations, and thereby address the stated research gaps for the geography of the global south and also for electric vehicle application in the public transport and micro-mobility options.

This paper is structured into six sections. Section “[The SOLUTIONSplus Project](#)” describes the demonstration actions related to passenger transport within the SOLUTIONSplus project and the stakeholder priorities for the demonstration actions. Section “[Literature Search](#)” provides a literature review of the EVs in terms of key impact indicators. Section “[Methodology](#)” discusses the methodology used for assessing the impact indicators. Section “[The Analysis](#)” presents the analysis and section “[Conclusions and Policy Recommendations](#)” concludes.

The SOLUTIONSplus project

Demonstration actions

The SOLUTIONSplus project, as mentioned earlier, has implemented demonstration activities to enhance public transportation connectivity for passengers in Africa and

Asia. The demonstration actions in the SOLUTIONSplus project are described on the website: <https://www.solutionsplus.eu/living-labs>. The project website has a detailed description of demo cities and the demonstration actions that were undertaken within the living labs. The following demonstrations have taken place for passenger transport in the SOLUTIONSplus project:

- **e-three wheelers** (Dar es Salam, Tanzania) replace ICE models. The pilot focusses on three-wheeled vehicles (locally called “Bajaj’s”) that already provide passenger feeder services to the Bus Rapid Transit (BRT) system. In total, 39 e-three wheelers with various degrees of local design, manufacturing, and assembly activities, and 4 retrofitted ICE three-wheelers were part of the demo.
- **Safa Tempo** (Kathmandu, Nepal). A 11 seater 23-year-old Safa Tempo (e- three wheeler) has been remodelled to showcase improved vehicle performance, extended life of older vehicles and job security for mostly women drivers.
- **e-three wheelers** (Kathmandu, Nepal). The passenger version of a mini Safa Tempo (6 seater) aims to provide service to the secondary and tertiary routes of the city as a last mile connectivity.
- **e-moto taxis** (Kigali, Rwanda) were introduced, replacing ICE motorcycle taxis. The project had a strong gender-inclusive focus and trained women to become drivers of motorcycles, before handing over 24 e-moto to female beneficiaries.
- **e-mopeds** (Hanoi, Vietnam) for providing last mile connectivity between a BRT stop and a shopping mall. A total of 50 Vinfast Ludo e-mopeds were employed by the demo to substitute trips provided by a shuttle bus that operates on diesel.
- **e-shuttle van** (Kathmandu, Nepal) targets the historic areas and heritage routes of Kathmandu with 6 seats.
- **Bus conversion** (Kathmandu, Nepal) involves converting a diesel bus into e-bus by replacing diesel engine and installing batteries at the rear end.

Electric three-wheelers, mopeds, and buses for passenger transport face several barriers in developing countries across Asia and Africa where SOLUTIONSplus pilot projects were implemented. For electric three-wheelers, the main challenges include limited range, charging infrastructure, high upfront costs compared to conventional vehicles and a need for more financing options and government incentives [13]. Electric 2-wheelers for individuals face affordability concerns for low-income households [14], and the same can be the case for moto drivers. In addition, the safety and reliability issues of electric 2-wheelers are also significant barriers [5]. Due

to their large battery size, electric buses face a significant barrier in terms of high capital costs and limited financing options [5]. Electric bus charging happens typically at night, and therefore, the lack of a reliable electricity supply for charging is also a significant barrier in developing countries [15]. Addressing these barriers is crucial for the widespread adoption of electric vehicles in developing countries, which can contribute to sustainable transportation and reduce environmental impact. These barriers and objectives of the SOLUTIONSplus project were the key considerations for Key Performance Indicator identification.

Stakeholder priorities

Key Performance Indicators (KPIs) are used to evaluate the impact of demonstration projects. The KPI weights in the four demo cities appear in Table 1. They resulted from a 2-round Delphi method application involving 10–20 knowledgeable individuals in each city reflecting the corresponding stakeholder priorities. The indicators are organised into six Level-1 and 20 Level-2 KPIs. These are further divided into lower levels (3 and 4), which, however, are not shown here due to space limitations.

On average, the weights of the six Level-1 indicators appear balanced across the demo cities, ranging from 14.79 (climate) to 19.77 (society) per cent. Environment and climate stand out as the top priorities for Kigali, while societal and wider economic concerns attract the least weight. In Dar es Salaam, on the contrary, society and the wider economy share the top position, followed by environment and climate. Asian cities exhibit higher dispersion. The project’s financial performance attracts the highest stakeholder interest in Kathmandu, followed by the applicable institutional framework, probably signifying the entrance barriers of nascent technologies on top of the institutional/political realities of the country. Society has the highest weight in Hanoi, followed by the environment. Climate change appears to be the lowest priority in both Asian cities, probably due to its less visible effects.

Although no proper randomisation of the stakeholder sample was attempted, the participation of individuals from all stakeholder groups makes the results indicative of the city’s perceptions. In general, stakeholders have accorded high importance to financial viability, the effect of GHG emissions, the effect on air pollutants, the effect on accessibility and the effect on affordability KPI (Level 2); therefore, these are discussed further in the paper. The Level 1 KPIs on institutional framework and the wider economy are also important and have an impact on the possibility of scaling up the demonstration projects but will not be discussed here since the focus is on demo actions.

Table 1 KPI weights for the demo cities (stakeholders' input)

Level-1	Level-2	Kigali	Dar	Kath.	Hanoi	Avg.
Project finances	Financial viability	8.70	8.75	12.25	7.30	9.25
	Availability of finance	9.00	7.25	11.19	6.48	8.48
	<i>Project finances, total</i>	<i>17.70</i>	<i>16.00</i>	<i>23.44</i>	<i>13.78</i>	<i>17.73</i>
Institutional framework	Coherence with plans/goals	5.48	5.32	5.86	5.98	5.66
	Alignment with legislation	3.91	4.48	5.40	4.61	4.60
	Ease of implementation	6.01	4.50	6.39	4.79	5.42
	<i>Institutional framework, total</i>	<i>15.40</i>	<i>14.30</i>	<i>17.65</i>	<i>15.38</i>	<i>15.68</i>
Climate	Effect on GHG emissions	18.40	16.20	13.19	11.35	14.79
Environment	Effect on air pollutants	7.56	4.97	6.37	7.08	6.50
	Effect on noise	5.69	4.73	4.26	4.02	4.67
	Effect on resource use	5.25	7.20	4.84	5.10	5.60
	<i>Environment, total</i>	<i>18.50</i>	<i>16.90</i>	<i>15.46</i>	<i>16.20</i>	<i>16.77</i>
Society	Effect on accessibility	1.92	2.86	2.04	4.47	2.82
	Effect on affordability	2.16	2.01	2.16	3.11	2.36
	Effect on travel time	2.04	2.57	1.36	4.73	2.68
	Effect on road safety	1.87	2.20	1.60	4.11	2.45
	Effect on charging safety	1.50	1.85	1.79	3.06	2.05
	Effect on security	1.56	2.01	1.23	3.07	1.97
	Effect on well-being	1.94	2.32	1.68	2.71	2.16
	Effect on service quality	2.21	2.48	1.94	6.50	3.28
	<i>Society, total</i>	<i>15.20</i>	<i>18.30</i>	<i>13.81</i>	<i>31.76</i>	<i>19.77</i>
	Wider economy	Effect on budget	5.02	5.68	6.09	4.56
Effect on external trade		5.17	5.83	5.64	3.03	4.92
Effect on employment		4.61	6.79	4.71	3.94	5.01
<i>Wider economy, total</i>		<i>14.80</i>	<i>18.30</i>	<i>16.44</i>	<i>11.53</i>	<i>15.27</i>
	<i>Grand total</i>	<i>100.00</i>	<i>100.00</i>	<i>100.00</i>	<i>100.00</i>	<i>100.00</i>

Literature search

E-mobility and financial viability

It is generally accepted that battery electric vehicles (BEVs) are more expensive to buy and less expensive to operate than internal combustion engine (ICE) vehicles. The reality, however, is more complex and changes fast. In view of the drastic reduction of battery costs over the past decade, the National Academies (2021) of the USA [16] project that the period 2025–2035 can ‘... bring the most fundamental transformation in the 100-plus year history of the automobile’ as the purchase costs of BEVs are likely to reach parity with those of ICE vehicles. Other related costs that a first-time owner of an EV may face are the cost of installing a charger and the potential cost of switching electricity tariffs [17].

In terms of operational costs, where EVs have a definite advantage, savings depend heavily on electricity and fuel prices, leading to significant variations across locations and over time. Rapson et al. [17] mention that the top marginal retail electricity price can range from 10.5 to 37.0 € cents per kWh even within the municipality of Sacramento, while gasoline prices vary substantially over time (due to wide fluctuations in the price of crude oil) and across locations (due to state-level regulations, excise taxes and proximity to refining capacity). Savings, albeit generally low, also result from maintenance costs due

to the much fewer moving parts of an electric motor in comparison to an ICE. It should be noted, though, that the return on investment (ROI) heavily depends on the expected mileage of the vehicle, which in turn reflects its type and operational profile.

Regarding developing countries, a recent World Bank study across 20 countries finds that more than half would benefit economically from e-mobility in passenger transport [18]. In some countries this results merely from the lower operating and maintenance costs, while in others, the environmental benefits need also to be considered. Countries with lower-cost vehicles (such as two- and three-wheelers) and those that are net oil importers will benefit the most.

E-mobility and climate impacts

The climate impacts of EVs will depend upon the fuels used in the vehicles in the baseline scenario and the energy efficiency of the vehicles. Currently, gasoline and diesel fuels remain the dominant fuels used in the light-duty vehicle (LDV) segment, and for buses, it is diesel [19]. The tailpipe GHG emissions of BEVs are zero. However, the picture is not so clear when we look at the well-to-wheel or if we go for life cycle emissions, since in such cases the GHG reduction will depend on the GHG intensity of electricity production. There have been many life

cycle assessments undertaken covering different vehicles (LDVs/buses) and in different country contexts [1]. These studies show that when electricity is produced using coal—for an LDV, the median GHG emissions are not much better than gasoline and diesel vehicles; however, BEV buses are better than diesel buses. When electricity is produced using natural gas, the GHG emissions of BEV in both LDV and buses are much lower than ICE engines using gasoline or diesel. As we shift electricity production to renewables, BEV starts emerging as a near-zero GHG emission technology.

E-mobility and environmental impacts

Vehicles (LDVs/buses) that run on gasoline and diesel (the dominant fuel used currently) produce local pollutants such as NO_x, PM_{2.5}, PM₁₀, etc, and road transport generates a significant share of emission load in cities in developing countries [20]. The local pollution in many cities of the developing world is way beyond the standards for air quality set by WHO [21]. The local environmental impacts of BEVs are zero at the tailpipe and, therefore, can significantly impact the improvement of local air quality in the cities where these vehicles operate. However, local pollution from vehicles running on gasoline and diesel vehicles can also be reduced through the implementation of stricter vehicle and fuel standards (See Table 2), and many developing countries are taking this route. The phasing out of leaded gasoline was already achieved in 2021, and now the next target is to move all countries below 50 ppm of sulphur in diesel [22]. Due to improvements such as these in fuels and vehicles running on gasoline and diesel, the potential environmental impacts of BEV in the future are expected to be lower.

E-mobility and social impacts (accessibility, travel times, affordability)

The adoption of electric mobility solutions, such as e-scooters, e-three wheelers, and e-buses, in developing countries across Asia, Africa, and Latin America has the potential to create significant social impacts. These impacts can be both positive and negative, influencing

various aspects of society, including employment, accessibility, health, and social equity.

The shift toward electric mobility can improve accessibility for people in urban areas, as e-scooters and e-three wheelers provide affordable and convenient last-mile transportation options [23].

The concept of accessibility, initially defined by Hansen [24] as a measurement of individuals' potential opportunities to reach desired destinations, offers critical insights into evaluating the impact of new transportation modes and options relative to land use and socio-economic factors. This framework is pivotal when analysing e-mobility from a perspective of transport geography to understand its role in enhancing people's mobility and, consequently, accessibility across various urban settings. In the urban contexts of South Asia and Sub-Saharan Africa, two- and three-wheelers are notably instrumental in providing transportation options, thereby facilitating access to essential locations [25–27].

Accordingly, the primary impacts of electric LDVs on accessibility are likely to be shaped by factors that govern their usage areas, driven by regulatory considerations. Through this lens, electric light vehicles represent a promising advancement in transportation technology, potentially fostering greater accessibility in urban environments by mitigating some of the traditional barriers associated with their ICE-powered counterparts.

However, introducing electric mobility solutions can also result in negative social impacts. For instance, adopting e-buses may lead to job losses for traditional bus drivers and conductors and workers in the fossil fuel industry [28].

Moreover, the unregulated growth of e-scooters and e-three-wheelers can create safety concerns for pedestrians and other road users, particularly in cities with inadequate infrastructure [29].

Electric mobility offers the potential for improved travel times through enhanced vehicle performance and reduced congestion. Electric vehicles have better acceleration and should result in reduced travel times, so for setting where dedicated lanes are available for public transport, electric vehicles are more effective in reducing

Table 2 Air pollutant emission standards for ICE vehicles

Air pollutant emission standards (g/km)	EURO I	EURO II	EURO III	EURO IV	EURO V	EURO VI
2&3 Wheelers						
PM emissions gasoline ICE	0.100	0.100	0.100	0.100	0.045	0.023
NO _x emissions gasoline ICE	0.300	0.300	0.150	0.070	0.060	0.045
Buses						
PM emissions diesel ICE	0.36	0.15	0.13	0.02	0.02	0.01
PM emissions CNG ICE	0.18	0.08	0.07	0.01	0.01	0.01
NO _x emissions diesel ICE	8.00	7.00	5.00	3.50	2.00	0.40
NO _x emissions CNG ICE	4.00	3.50	2.50	1.75	1.00	0.20

Source UNEP e-Mobility calculator for e-2/3 wheelers and e-buses

travel times [14]. However, in mixed traffic conditions, no change or very little change in travel times is expected [30].

The higher capital cost of electric vehicles can be a challenge in developing countries, however, electric two wheelers and three wheelers are more attractive in terms of capital costs [31], also the price of electricity is lower compared to the price of gasoline, and electric vehicles also have higher operation and maintenance saving compared to ICE vehicles, which make them overall more affordable as compared to ICE vehicles [32]. Another important social impact to consider is the potential widening of the digital divide. Access to electric mobility solutions may be limited to those who can afford them or possess the necessary digital literacy skills. This situation can exacerbate existing social inequalities and hinder the equitable distribution of the benefits of electric mobility [33].

Methodology

Financial assessment

The classical financial cost-benefit analysis (CBA) is the approach followed for the financial assessment of the demonstration vehicles, necessitated by the aim of ultimately developing bankable e-mobility projects in the demo cities. Unlike the multi-criteria decision analysis (MCDA) approach selected for assessing the remaining sustainability dimensions, which takes a societal viewpoint, the perspective of the financial analysis is this of an investor or operator of the vehicles assessed.

Two different methodologies are applied for the financial assessment, depending on the type of project examined (profit maximising or cost minimising operation). Commercial applications undertaken by private operators are usually profit maximising projects. In these cases, both revenues and out-of-pocket costs need to be estimated for the entire life duration of the project. The indicators used for such cases are the Net Present Value (NPV), Internal Rate of Return (IRR) and the Payback Period.

Reflecting the present worth of an investment, NPV is defined as the sum of all future cash flows discounted at a periodic rate of return to account for the time value of money. A positive NPV indicates that the projected earnings generated by the project exceed the anticipated costs and the project can be accepted. IRR denotes the rate of return that sets the net present value of the future cash flows of a project equal to zero. An IRR higher than the opportunity cost of the project owner indicates a profitability that exceeds the expected one from other activities and suggests the undertaking of the project. Payback period denotes the time required to recover the funds expended in an investment. It does not consider the time value of money, a fact that makes it easy to apply

and comprehend. However, it is not considered by the financing institutions as formal as the other two indicators. Among these two, IRR was selected for the present application given its independence from the size of the investment.

On the other hand, for cost minimising projects, mainly in the public sector, where revenues either do not exist or are very difficult to monetise, the Cost Effectiveness Ratio (CER) is used. The method estimates the costs of the project and relates them to its primary outcome in terms of 'units of effectiveness' (e.g., number of lives saved, volume of waste collected, etc.). CER is obtained by dividing total costs by the units of effectiveness. The lower a project's CER is, the more desirable its undertaking becomes.

Climate assessment

The impact on climate is measured in terms of the greenhouse gas (GHG) emissions reduced or avoided during the lifetime of vehicle. There are multiple GHG's (CO_2 , CH_4 , N_2O , HCFCs, etc) and here we will calculate only CO_2 emissions from the BEV and compared to the baseline scenario. The GHG emissions are calculated well-to-wheels (including CO_2 emissions in electricity production). In general, to obtain the CO_2 reduction, a formula that identifies CO_2 emissions per operational unit [Km] for both the BEV and the ICE (baseline solution) is required. These will be impacted by the total Km travelled (Average lifespan of mode of transport).

$$CO_2 \text{ reduced} = [CO_2 \text{ per km ICE} - CO_2 \text{ per km BEV}] \times VKM$$

where:

- $CO_2 \text{ reduced}$ is the amount of CO_2 emissions reduced during the life of the BEV
- $CO_2 \text{ per km ICE}$ are well to wheel CO_2 emissions per km travelled for the ICE baseline vehicle
- $CO_2 \text{ per km BEV}$ are the CO_2 emissions associated with the BEV per km travelled.
- VKM is the total km run during the life of BEV.

Further:

$$CO_2 \text{ per km ICE} = el * F0$$

where:

- el is the CO_2 emissions per litre of fuel [$\text{Kg CO}_2/\text{L}$]
- $F0$ is the fuel consumption of ICE vehicle [L/Km]

$$CO_2 \text{ per km BEV} = es * Em$$

where:

- e_s is the emission factor of the electricity source [Kg CO₂/kWh]
- E_m is the energy consumption of the e-mobility solution in [kWh/Km].

Environmental assessment

The reduction in PM and NO_x emissions is achieved by replacing ICE engines with BEVs since ICE vehicles have emissions (Table 2), whereas BEVs have no such pollution at the point of use. The NO_x and PM calculations are based on a tank-to-wheel basis, focusing only on the operational phase, and do not account for NO_x emissions during production, (battery) manufacturing, or disposal stages.

The formula for NO_x emissions avoided is:

$$NO_{x \text{ avoided}} = (NO_{x \text{ stock ICE}} - NO_{x \text{ stock BEV}}) * VKM$$

where,

- $NO_{x \text{ avoided}}$ is the amount of NO_x emissions avoided during the use phase of the product,
- $NO_{x \text{ stock ICE}}$ is the average NO_x emissions (gm/Km) from ICE vehicles running on fossil fuels (such as gasoline/ diesel/ CNG). Note that changes in NO_x emission will happen due to changes in fuel standards over time. UNEP eMob calculator can directly calculate this value, based on stock vintages and emissions standards.
- $NO_{x \text{ stock BEV}}$ is considered as zero since we are only analysing the tank to wheel emissions
- VKM is the total km run during the life of BEV

The UNEP e-Mob calculator [34] is used to analyse the impact of SOLUTIONSplus interventions on GHG emissions and air pollution in Dar es Salam and Kigali. UNEP e-Mobility calculator allows developing scenarios at city scale, modelling changes in stock based on vehicle vintages and doing demand projections. However, in other cities the same approach was followed albeit through customised Excel spreadsheets.

Social impacts assessment (accessibility, travel time)

The methodology for accessibility is centred on evaluating the ease with which individuals can access public transport, emphasizing the concept of “Distance to Transit”, which aligns with Sustainable Development Goal (SDG) 11.2. This involved calculating the proportion of the population within a specified distance of a public transit stop – 500 meters for low-capacity modes and one kilometre for high-capacity modes [35].

To achieve this, a comprehensive dataset is used, including detailed area maps, grid-based population distribution data, the existing transport network layout

(including roads and sidewalks), and the precise locations of public transport stops. We then employed routing algorithms to determine the shortest path from each grid cell to the nearest public transport stop, both for the existing network and the enhanced network incorporating new services.

The assessment utilized officially recognized city boundaries to define the geographical scope. Population data was sourced from the World Settlement Footprint [36] while information on the transport network and public transport stops was extracted from Open Street Map and local GTFS files. Finally, accessibility computation using the UrMo Ac tool [37] is done and the PtAc SDG 11.2 wrapper [38], providing a thorough examination of how these demonstration actions impact accessibility for passengers.

For the paper, no affordability impact assessment was done since, in all the demonstrations, the fares of EVs were the same as the baseline vehicle. For travel time the impact focused only on the percentage change in (personal) travel times due to e-mobility services.

The KPI on change in (personal) travel times due to e-mobility services shows, for a predefined “typical route”, the percentage change in the average travel time between the baseline and e-mobility service scenarios. The calculation of this KPI uses the following steps: (1) Define the geographic boundaries for the analysis; (2) Define transport mode to be used under the baseline scenario for selected boundaries (e.g., dominant, or a mix of alternatives); (3) Measure total travel time (min) on the predefined route under the baseline scenario; (4) Measure the total travel time for the e-mobility solution(s) assessed; (5) Calculate the percentage difference in travel time between baseline and e-mobility service scenarios.

The analysis

Financial viability of electric vehicles

Five of the seven vehicles examined in this paper earn revenues, and their financial performance can be assessed through the IRR values of the corresponding investments. They consist of the converted bus in Kathmandu, three e-3Ws of different sizes in Kathmandu and Dar es Salaam, and the e-moto taxi in Kigali. Figure 1 depicts the obtained IRR values. The remaining two vehicles of the sample (the e-shuttle van in Kathmandu and the e-moped in Hanoi) are discussed separately.

At a cost of about €60,000 (Dec. 2022), the converted minibus, with a capacity of 50 passengers, is expected to perform three round trips (96 km in total) daily for the coming 10 years. It is expected to carry 366 passengers per day, earning the equivalent of €16,000 per year. This operating profile leads to a pre-tax IRR of 8.8%. Under comparable conditions (same capacity utilization ratio), the return of a new e-bus costing €93,000 and carrying 60

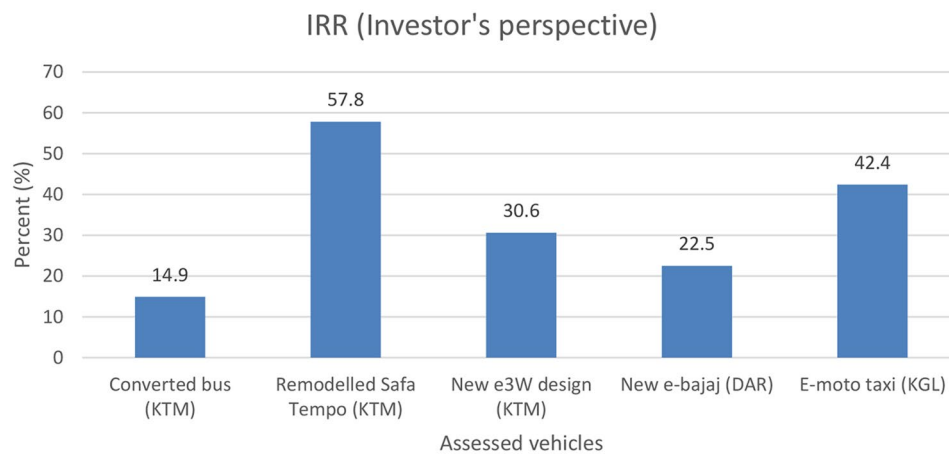


Fig. 1 Financial performance of the revenue-earning vehicles examined

passengers is 13.8%, while that of a new diesel bus worth €35,000 (capacity of 70 passengers) is 30.1%. Note that the profitability of the diesel bus is reversed when externalities are considered. Furthermore, when introducing economies of scale to the conversion activity (30% reduction in the conversion cost, accompanied by a 10% profit margin for the manufacturer), the IRR of the investment rises to 14.9%, which is comparable to that of the new e-bus, though achieved with less than 65% of the investment requirements.

Smaller vehicles exhibit higher returns. At a cost of €13,760, a 23-year-old Safa Tempo (e-3W carrying up to 11 passengers) in Kathmandu can be remodelled, including the replacement of the old lead acid battery set with a Li-ion battery, the replacement of motors and other components, new body works and upgrading the passenger cabin to make riding more comfortable. The deployment of the vehicle on a typical route for six years generates a healthy pre-tax IRR of 57.8%. This is the expected return of an investor who buys the remodelled vehicle directly from the manufacturer. It is worth checking, however, whether the owner of an existing unit under operation has a financial incentive to proceed with the remodeling. To investigate this scenario, the expected return of an existing Safa Tempo is estimated, and the resulting net present value enters the previous assessment as a cost (foregone profit). The IRR now drops to 40.2%, which confirms the financial soundness of the remodeling. Under analogous operating conditions, a new e-3W design in Kathmandu, that costs €8120 and carries up to 6 passengers, exhibits an IRR of 30.6%, while a smaller e-3W design (e-bajaj) in Dar es Salaam that seats only two passengers and costs €5930 generates a return of 22.5%. Note the dropping tendency of IRR with vehicle size for the three e-3Ws, apparently due to investment increasing with size at a slower rate than that of revenues earned.

The sample e-motos in Kigali are operated as taxis through a different business model. The driver acquires a vehicle from the vendor company through various financial schemes such as lease-to-own, rental or outright purchase, at an equivalent unit cost of €1135 (Dec. 2021). The same vendor owns the batteries, which are provided and charged to the driver at a standard fee through a battery-swapping scheme. Seen from the driver's perspective, the operation generates a profitable pre-tax IRR of 42.4%. It is worth noting, however, that the profitability of all these light vehicles, measured through the IRR, strongly depends on the demand (revenues earned) due to the very low initial investment.

Among the non-revenue-earning vehicles, the e-shuttle van in Kathmandu is a 6-seater intended for transporting tourists to the Bhaktapur historical sites either at a fare or not. Purchased at a price of about €17,800 (Dec. 2022), the vehicle is expected to be operational for 12 years. Its battery, enabling a range of more than 100 km per day, needs to be replaced after six years. At a fare equal to that of regular bus services, the expected average ridership of 100 passengers per day is sufficient to cover only the operating expenses making losses when the capital costs enter the calculation. If the envisioned service is offered for free, the CER methodology is applied, resulting in a ratio of 30.79 Nepalese Rupees (NPR) per passenger. When compared to the CER value associated with an existing open-type van operated by a local municipality for transporting elderly/disabled people (85.75 NPR/passenger), the new design corresponds to an impressive 64.09% reduction. However, once again, this result is very sensitive to the capital costs and the number of passengers served.

The e-mopeds in Hanoi were introduced to connect a BRT stop with a shopping mall, which is served by a diesel-run shuttle bus free of charge. During the demonstration period, an average of about 14 e-moped trips per day

was observed for the busiest months. The non-revenue-earning nature of the service called for a CER application. Unfortunately, though, no information on the shuttle bus operation became available, rendering any benchmarking activity infeasible. It was estimated, however, that a daily number of 275 trips would be required for the e-moped operation to break even. This estimate is much higher than the demo performance.

Climate impacts of electric vehicles

The GHG emissions are calculated well-to-wheel (including CO₂ emissions in electricity production) and depend on the base case option. As the e-motos in Kigali and e-Bajaj in Dar es Salaam replace old ICE vehicles, they result in significant GHG emission reduction of 73% and 83%, respectively, from the base case technology in the base year. The reductions are higher in the case of Dar es Salaam compared to Kigali (Fig. 2) since the three-wheelers used in Dar es Salaam are larger compared to 2 wheeler motorcycles used in Kigali. Further, the CO₂ emissions intensity for electricity in Dar es Salam is 260 gm CO₂/Kwh, much lower than Kigali's 460 gm CO₂/Kwh. In the analysis, no change in CO₂ intensity of electricity is considered with time, though gradual improvements in ICE engines are considered. In Dar es Salaam, considering an annual mileage of 30,000 km per vehicle, the CO₂ reduction drops from around 2.31 t CO₂ in 2023 to 2.24 t CO₂ in 2033. In the case of Kigali, considering an annual mileage of 48,984 km per vehicle, CO₂ reduction drops from around 2.54 t CO₂ in 2023 to 2.27 t CO₂ in 2033.

In Hanoi, since the base case technology is a shuttle bus with an occupancy of 10 persons in comparison to one

for e-mopeds, a slightly modified approach was considered and instead of VKMs, passenger kilometres (PKMs) were used to ensure comparability across the two different modes. The e-mopeds can reduce CO₂ emissions by 55.8 gm CO₂ per PKM (i.e., by 87.5%) from the baseline technology (shuttle bus) in the base year. The e-mopeds cover a trip length of 2.2 km and an average of 262 rides per month, and based on this, the annual reduction due to the demo was only 0.38 t CO₂. The emission reduction can increase further if the emission intensity of electricity is reduced from the current level of 521 gm CO₂/Kwh. In Kathmandu, no major CO₂ impact is expected from the two 3Ws (the remodelled Safa Tempo and the smaller new design), as they replace an older electric vehicle (Safa Tempo).

In Kathmandu, for the newly designed shuttle van, the equivalent existing ICE vehicle is a microbus run on diesel. The yearly CO₂ emissions of this microbus and for the same mileage are estimated at 15.1 t CO₂. Similarly, for the bus conversion, the equivalent existing ICE vehicle is a bus run on diesel. The yearly CO₂ emissions of this bus and for the same mileage are estimated at 15.1 t CO₂. In Kigali, the base case technology for the e-buses is diesel. The yearly CO₂ emissions (in 2023) of the diesel bus are estimated at 57.9 t CO₂ compared to 4.55 t CO₂ for an e-bus. The CO₂ emissions are, therefore, 92% lower for an electric bus.

Environmental impacts of electric vehicles

In terms of NO_x and PM_{2.5} emissions, based on tank-to-wheel analysis, the reductions are 100% from the base case since EVs have no tailpipe emissions. However, the absolute NO_x and PM_{2.5} reductions decline with time

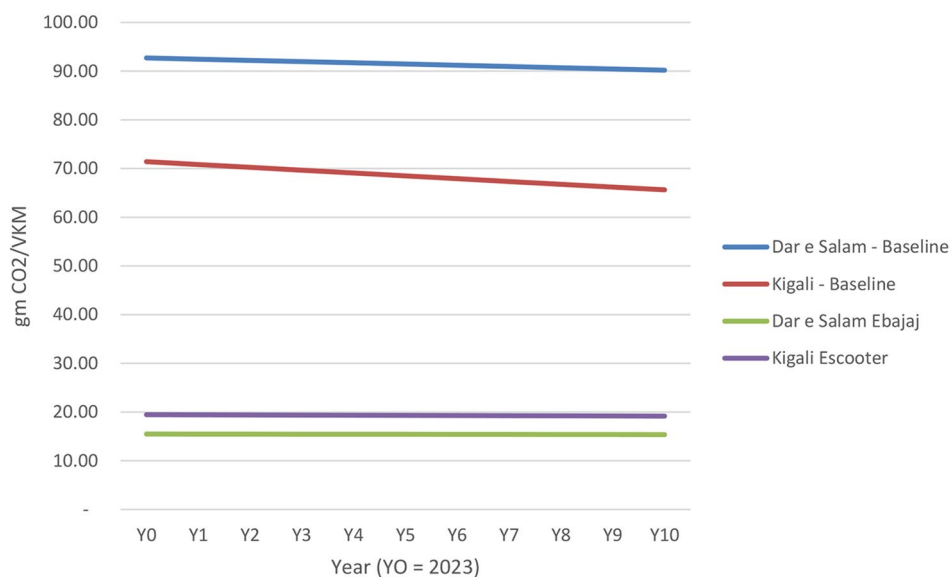


Fig. 2 CO₂ emissions – Dar es Salaam vs Kigali

(Fig. 3) since there is improvement in the emission standards for ICE vehicles as well, e.g., annual NOx emission per vehicle in Kigali declined from 5.75 kg NOx per annum in 2023 to only 3.48 kg in 2033. In Kathmandu, no major environmental impact is expected from the two 3Ws (the remodelled Safa Tempo and the smaller new design), as they replace an older electric vehicle (Safa Tempo). In Hanoi, the absolute NOx and PM10 are 0.04 kg PM10 and 1.95 kg NOx respectively.

In Kathmandu, for the newly designed shuttle van, the equivalent existing ICE vehicle is a microbus run on diesel for which the yearly NOx and PM2.5 emissions are 70.1 and 24.2 kg/year. Similarly, for the bus conversion, the equivalent existing ICE vehicle is a bus run on diesel. The yearly NOx and PM2.5 emissions are 201.3 and 52 kg/year, respectively. In Kigali, for the e-buses the equivalent base case technology is a diesel bus. The yearly NOx and PM2.5 emissions are 255.1 and 9.2 kg/year respectively. However, due to improvements in vehicle stock with time (on account of improved fuel standards) the emissions would decline especially for NOx and PM2.5. For example, in 2033 PM2.5 emissions from a diesel bus would come down to only 1.1 kg/year.

Social impact assessment (accessibility, travel time) of electric vehicles

Through comprehensive evaluation, it became apparent that only in Dar es Salaam could the quantitative impacts on accessibility be reliably estimated. This distinction arose since the e-mobility initiatives in Kigali and Kathmandu predominantly focused on converting or upgrading existing vehicles, rather than augmenting the urban mobility framework. Conversely, Dar es Salaam’s demonstration action entailed a tangible expansion of the city’s public transport network, proposing the integration of electric three-wheeler feeder routes along four key corridors.

In Dar es Salaam, our methodology involved analysing the hypothetical implementation of these feeder routes and their ensuing synergy with the existing Bus Rapid Transit (BRT) system. The Sustainable Development

Goal (SDG) 11.2 indicator under two distinct scenarios: one consisting of the BRT infrastructure alone, and another encompassing both the BRT and the proposed feeder routes. Findings, illustrated in Fig. 4, reveal a notable increase in accessibility due to this integrated approach. Initially, the SDG 11.2 indicator, calculated based on the BRT corridor alone, stood at 15%, indicating that merely 15% of the urban population had convenient access to public transit. The incorporation of the electric three-wheeler routes, when viewed as an augmented component of a cohesive transport network, elevated this metric by 4.5 percentage points, culminating in a revised accessibility rate of 19.5%. This analytical outcome underscores the potential of integrating novel e-mobility solutions into existing urban transport systems to significantly enhance public transport accessibility.

As the travel routes and fares remained same no effects are expected in terms of affordability or travel time in all demo activities except in Hanoi, where the total travel time for the e-moped is shorter due to the avoidance of the waiting time for the shuttle bus. In Hanoi, the travel times for the e-mopeds and shuttle bus were assumed to be the same (5 min), given that the route was the same. However, the expected waiting times and alighting times varied for both solutions. The change in travel time ($TT_{change(\%)}$) for the e-mopeds in Hanoi is then computed as:

- $T_{wait\ moped}$ assumed to be 5 min (for putting helmet and retrieving e-mopeds)
- $T_{alight\ moped}$ assumed to be 5 min (for removing helmet and parking e-mopeds)
- The waiting time for the shuttle bus varies across the day, as the number of departures per hour changes throughout the day. The shuttle bus schedule, obtained from the local mall’s app, was used as a reference for computing the average waiting time. Assuming arrivals happening with the same likelihood in 5-min intervals between the first departure (10 a.m.) and the last one (9 p.m.), an average waiting time of 16 min was obtained.

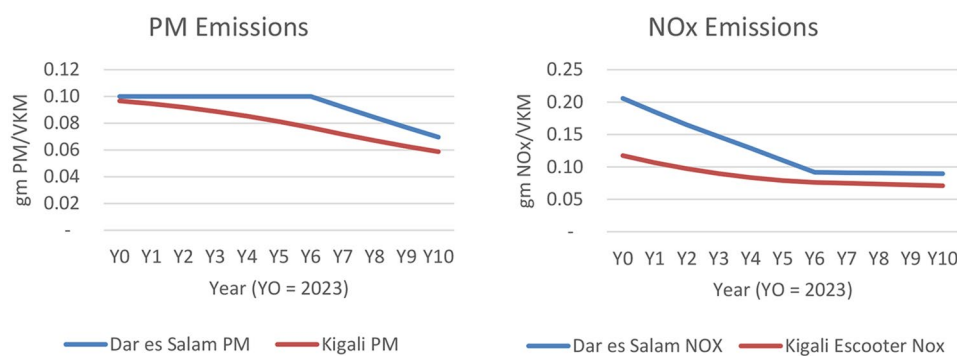


Fig. 3 PM and NOx emission reductions (per VKM) for Dar es Salaam vs Kigali

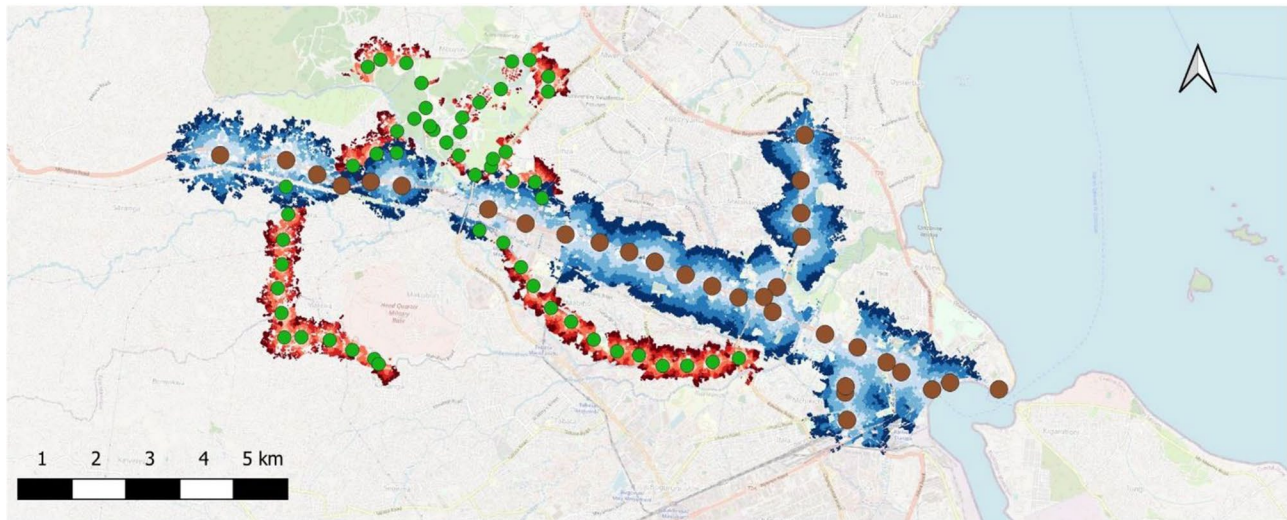


Fig. 4 Map of Dar es Salaam illustrating the results of an accessibility analysis using the SDG 11.2 standard. Blue areas indicate the catchment areas accessible within a 1 km distance to the BRT (Bus Rapid Transit) system, while red areas indicate the 500 m catchment areas for three-wheeler corridors. The brown dots are the locations of the BRT stations or stops, and the green dots are the locations of the three-wheeler stops

- $T_{\text{align shuttle}}$ was deemed to be zero (as upon arrival, travellers can alight the shuttle and continue to the mall immediately, without any extra time required).

Conclusions and policy recommendations

The SOLUTIONSplus project involved demonstration actions related to passenger transport in several cities in Asia and Africa. All the demonstration actions were related to public transportation service. The stakeholders within each city and country had multiple objectives from these demonstration projects and a long-term goal of scaling up these demonstrations. In this paper the demonstrations are analysed from their financial viability, climate impacts, environmental impacts and key social impacts.

Light-duty EVs turn out to be financially viable when they replace existing vehicles running established profitable operations (routes are pre-defined, fares are already decided, and the demand is given). Their profitability, however, is very sensitive to the demand (revenues earned) due to the very low initial investment. The demonstration activities in Kathmandu and Dar es Salaam have shown that for a specific type of vehicle (e-three wheelers in this case), returns (as expressed by IRR) are inversely related to vehicle size, as acquisition and operating costs do not increase with size as fast as the revenues do. Concerning larger vehicles, the Kathmandu demonstration activities have demonstrated that the conversion of diesel buses to e-buses can become financially viable only when sufficient economies of scale can be achieved. The battery cost reductions have made the electric vehicles cost competitive; however for policymakers and project developers looking to scale up electric vehicles, the following is recommended

- A detailed analysis of traffic demand on the routes where electric vehicles are going to be introduced should be done. A practical approach is to replace conventional vehicles that are running a profitable operation.
- Financial viability of electric vehicles has also been in some cases been due to favourable tax policies and in case the government want to withdraw these then it should be done in a transparent and phased manner to avoid increasing risks and uncertainties for market players
- The operating costs of EVs are much lower than those of conventional vehicles, and a large part of this is attributable to electricity. Hence maintaining a stable electricity price can reduce the uncertainties for electric vehicles
- Electric bus systems are much more expensive in terms of upfront costs and hence financial viability can be ensured by running only on routes with a high traffic.

EVs are an efficient technology, and on a well-to-wheel basis, all the demonstration actions in different electricity grids (Vietnam, Nepal, Tanzania and Rwanda) resulted in reducing CO₂ emissions. This clearly establishes that EVs are a mitigation option for now and in the future as electricity grids become less CO₂ intensive. EVs have zero tailpipe emissions and, therefore, will help in reducing air pollution in cities in developing countries where air quality is quite poor in many cities. However, in the long term, the benefits will be lower since lead pollution in gasoline ended in 2021 in all countries, and progressively, countries are reducing the sulphur content of fuels. The positive externalities of EVs in terms of lower

CO₂ emissions are significant, and the following are recommended to internalise the positive externalities.

- City governments should set up online platforms to report the CO₂ reductions and local environmental benefits from EV implementations. These platforms should also openly provide the methodology used for estimating the reductions.
- City governments should improve awareness about the benefits of EVs by conducting campaigns.
- Government at the national level can provide financial incentives that are linked to the benefits of EVs. In a similar fashion, city governments can provide incentives for parking in traffic and create zones only accessible to EVs
- Clear timelines should be laid out for the phase-out of fossil fuel-based vehicles used for public transport

As indicated by the Dar es Salaam demonstration, significant accessibility improvements can be achieved when light vehicles are used as feeders to the main urban transport modes. In terms of travel time, e-mobility cannot make a big difference, as general traffic conditions comprise the decisive factor. As the Hanoi demonstration has shown, however, time gains can be achieved by readily available e-mopeds that replace larger vehicles operated on specific schedules.

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Author contributions

SD, TM and GP designed the study together; EM and SS were led for demonstration actions in cities and facilitated the data collection from the city side. GP/MB contributed towards financial assessment, SD contributed to climate and environmental assessment, MG contributed towards accessibility assessment, and TM / AC contributed towards social impacts assessment. The writing work was a joint effort by the entire team.

Data availability

No datasets were generated or analysed during the current study.

Declarations

Competing interests

The authors declare no competing interests.

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References

1. Jaramillo P, Ribeiro SK, Newman P, Dhar S, Diemuodeke O, Kajino T, et al. Chapter 10 Transport. In: Climate Change 2022: Mitigation of Climate Change Working Group III Contribution to the IPCC Sixth Assessment Report. 2022.

2. REN21. Renewables 2023 Global Status Report Collection, Renewables in energy demand [Internet]. 2023. Available from: <https://www.ren21.net/gsr-2023/>.
3. ITF. Transport outlook 2023 [Internet]. Paris; 2023. Available from: <https://www.itf-oecd.org/sites/default/files/repositories/itf-transport-outlook-2023-summary-en.pdf>.
4. Virta. The global electric vehicle market overview in 2024: statistics and forecasts [Internet]. 2024. Available from: <https://www.virta.global/en/global-electric-vehicle-market>.
5. Munshi T, Dhar S, Painuly J. Understanding barriers to electric vehicle adoption for personal mobility: a case study of middle income in-service residents in Hyderabad city, India. *Energy Policy*. 2022;167.
6. Rezvani Z, Jansson J, Bodin J. Advances in consumer electric vehicle adoption research: a review and research agenda. *Transp Res Part D Transp Environ*. 2015;34.
7. Collett KA, Hirmer SA, Dalkmann H, Crozier C, Mulugetta Y, McCulloch MD. Can electric vehicles be good for Sub-Saharan Africa? *Energy Strategy Rev*. 2021;38.
8. Martin E, Courtright T, Nkurunziza A, Lah O. Motorcycle taxis in transition? Review of digitalization and electrification trends in selected East African capital cities. *Case Stud Transp Policy*. 2023;13.
9. Galuszka J, Martin E, Nkurunziza A, Oginga JA, Senyagwa J, Teko E, et al. East Africa's policy and stakeholder integration of informal operators in electric mobility transitions—Kigali, Nairobi, Kisumu and Dar es Salaam. *Sustain*. 2021;13(4).
10. Sovacool BK, Daniels C, AbdulRafiu A. Transitioning to electrified, automated and shared mobility in an African context: a comparative review of Johannesburg, Kigali, Lagos and Nairobi. *J Transp Geogr*. 2022;98.
11. Hasselwander M, Senyagwa J, Martin E, Andrieu VM, Goletz M, Lah O. Vehicle electrification in informal transport. *Urban Transitions Global Summit 2022*. 2022.
12. Panagakos G, Goletz M, Hasselwander M, Mejia A, Aittoniemi E, Barfod MB, et al. E-mobility solutions for urban transportation: user needs across four continents. *Transp Res Procedia*. 2023;72:2558–65.
13. Al Hossain MJ, Hasan MZ, Hasanuzzaman M, Khan MZR, Ahsan Habib M. Affordable electric three-wheeler in Bangladesh: prospects, challenges, and sustainable solutions. *Sustainability*. 2022;15(1):149.
14. Rajper SZ, Albrecht J. Prospects of electric vehicles in the developing countries: a literature review. *Sustainability*. 2020;12(5):1906.
15. Blimpo MP, Cosgrove-Davies M. Electricity access in Sub-Saharan Africa: uptake, reliability, and complementary factors for economic impact. *World Bank Publications*; 2019.
16. National Academies of Sciences E and M. Assessment of technologies for improving light-duty vehicle fuel economy 2025–2035. *The National Academies Press*; 2021.
17. Rapson DS, Muehlegger E. The economics of electric vehicles [Internet]. Cambridge, Massachusetts; 2022. Report No.: Working paper 29093. Available from: <http://www.nber.org/papers/w29093>.
18. Rapson DS, Muehlegger E. The economics of electric vehicles. In: Review of environmental economics and policy. vol. 17. *World Bank Publications*; 2023. pp. 274–94.
19. IEA. World energy outlook 2019. Paris: International Energy Agency (IEA); 2019.
20. Guttikunda SK, Goel R, Pant P. Nature of air pollution, emission sources, and management in the Indian cities. *Atmos Environ* [Internet]. 2014;95(0):501–10. Available from <http://www.sciencedirect.com/science/article/pii/S1352231014005275>.
21. WHO. WHO ambient air quality database, 2022 update. 2023;34. Available from <https://iris.who.int/bitstream/handle/10665/368432/9789240047693-eng.pdf?sequence=1>.
22. EPA. Promoting cleaner fuels and vehicles worldwide [Internet]. 2024 [cited 2024 Jul 17]. Available from: <https://www.epa.gov/international-cooperation/promoting-cleaner-fuels-and-vehicles-worldwide>
23. Oeschger G, Carroll P, Caulfield B. Micromobility and public transport integration: the current state of knowledge. *Transp Res Part D Transp Environ*. 2020;89:102628.
24. Hansen WG. How accessibility shapes land use. *J Am Inst Plann*. 1959;25(2):73–76.
25. Ehebrecth D, Heinrichs D, Lenz B. Motorcycle-taxis in sub-Saharan Africa: current knowledge, implications for the debate on “informal” transport and research needs. *J Transp Geogr*. 2018;69:242–56.

26. Goletz M, Ehebrecht D. How can GPS/GNSS tracking data be used to improve our understanding of informal transport? A discussion based on a feasibility study from Dar es Salaam. *J Transp Geogr.* 2020;88:102305.
27. Owino F, Peters K, Jenkins J, Opiyo P, Chetto R, Ntramah S, et al. The urban motorcycle taxi sector in Sub-Saharan Africa: needs, practices and equity issues. *Urban Plan Transp Res* 2024;12:2354400.
28. Dobjani S. Exploring the impact of transitioning to e-buses on the public transport workforce: a case study of Metrobús Line 3 in Mexico City. Frankfurt University of Applied Sciences; 2024.
29. Jiao J, Bai S, Choi SJ. Understanding e-scooter incidents patterns in street network perspective: a case study of Travis County, Texas. *Sustainability.* 2021;13(19):10583. <https://doi.org/10.3390/su131910583>
30. Moon H, Park SY, Jeong C, Lee J. Forecasting electricity demand of electric vehicles by analyzing consumers' charging patterns. *Transp Res Part D Transp Environ.* 2018;62:64–79.
31. Weiss M, Dekker P, Moro A, Scholz H, Patel MK. On the electrification of road transportation—a review of the environmental, economic, and social performance of electric two-wheelers. *Transp Res Part D Transp Environ.* 2015;41:348–66.
32. Kumar P, Chakrabarty S. Total cost of ownership analysis of the impact of vehicle usage on the economic viability of electric vehicles in India. *Transp Res Rec.* 2020;2674(11):563–72.
33. Fleming KL. Social equity considerations in the new age of transportation: electric, automated, and shared mobility. *J Sci Policy Gov.* 2018;13(1):20.
34. UNEP. The eMob calculator [Internet]. United Nations Environment Programme; 2018. Available from: <https://www.unep.org/resources/toolkits-manuals-and-guides/emob-calculator>.
35. United Nations. SDG indicator meta data 11.2.1. [Internet]. 2021 [cited 2024 Jul 15]. Available from: <https://unstats.un.org/sdgs/metadata/files/Metadata-11-02-01.pdf>.
36. Palacios-Lopez D, Bachofer F, Esch T, Marconcini M, MacManus K, Sorichetta A, et al. High-resolution gridded population datasets: exploring the capabilities of the world settlement footprint 2019 imperviousness layer for the African continent. *Remote Sens* 2021;13:1142.
37. Krajzewicz D, Heinrichs D, Cyganski R. Intermodal contour accessibility measures computation using the 'UrMo Accessibility Computer'. *Int J Adv Syst Meas.* 2017;10(3&4):111–23.
38. Goletz M, Nieland S, Yosmaoglu S, Krajzewicz D. PtAC: using open and global data to contribute to SDG 11.2 monitoring by assessing accessibilities towards public transport. 2022.

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