

Can electric vehicles be good for Sub-Saharan Africa?

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ABSTRACT

Transport is an integral component of the energy system, and in Sub-Saharan Africa the demand for transport has been increasing due in part to population growth and economic development. To demonstrate the extent of this increased demand, emissions from transport in Africa grew by 84% over 6 years last decade [1] until, in 2018 in Sub-Saharan Africa, 15% of final energy consumption was demanded by the transport sector [2]. However, a global system change is underway for road passenger transport: a transition from polluting internal combustion engine vehicles to low-emission electric vehicles. Sub-Saharan Africa will not be immune to this transition, especially as a region which currently depends heavily on the import of second-hand vehicles [3]; not to mention the emission and air quality benefits electric vehicles can offer. Yet, by 2019 only 500 electric vehicles were on the roads in South Africa [4]. In this Viewpoint, we aim to dispel concerns that electric vehicles are always unaffordable and will cripple the already overloaded power systems in Sub-Saharan Africa. Instead, we propose that with innovative thinking and context-specific approaches and technologies, different from those in High-Income Countries, electric vehicles could in fact offer benefits to governments, the power systems, and vehicle owner-operators in Sub-Saharan Africa. We lay out how the historically siloed transport and electricity sectors could evolve to support each other in the future.

1. Introduction: why high-income country approaches to electrifying transport will not work in Sub-Saharan Africa

Electric Vehicles (EVs) in High-Income Countries (HICs) have several common characteristics: they are considered high-end, mass-manufactured, private passenger cars operating in urban areas, supported by national subsidies, and introduced with the confidence that the electricity sector will ensure there is sufficient generation to meet the demand they induce. By comparing these characteristics with the Sub-Saharan Africa (SSA) context, we identify three core reasons why HIC approaches to vehicle electrification should not be shoehorned into SSA: (i) the mobility patterns and vehicle characteristics of the transport systems, (ii) the availability of capital, and (iii) the unreliable state of the electricity systems.

Firstly, the characteristics of SSA transport systems are fundamentally different to those in HICs [5]. In SSA, the majority of journeys are undertaken using privately-owned and informally run “public” transport

vehicles, known as paratransit [6], which are demand-responsive, and often under-considered by transport planners [7]. Paratransit vehicles include motorbike taxis (e.g., boda-bodas), 16-seater minibuses (e.g., matatus), and auto-rickshaws (e.g., tuk-tuks) [8,9]. Paratransit vehicles meet the demand for 50–98% of automotive passenger trips in SSA cities [10]. In contrast, in the UK, 13% of automotive journeys are conducted using public transport while the vast majority (85%) are completed in private cars [11]. Given these differences between the transport systems, the private EV model is not suitable for the majority of transport needs in SSA. Instead, innovative approaches to SSA-specific EVs (e.g., minibuses and motorbikes) will need to be developed, along with appropriate business models, targeted at the paratransit vehicle owner-operators. Due to its dominance in SSA, this Viewpoint focuses on paratransit.

Secondly, the availability of capital is significantly lower in SSA than in HICs. Due to a lack of capital, the majority of vehicles are bought pre-owned from HICs. In Africa, 60% of annual registrations are of pre-owned vehicles [3]. In some countries, like Nigeria and Uganda, it can

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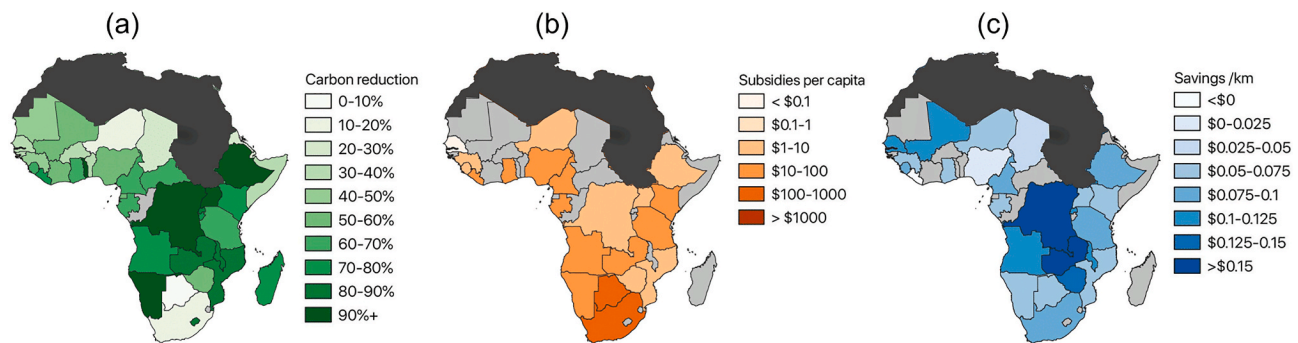


Fig. 1. Three maps of SSA to show (a) the emissions savings of operating an EV instead of an ICE considering current electricity generation profiles, (b) government spending on post-tax petroleum subsidies, which could be reduced and redistributed if EVs were adopted, and (c) the operational cost savings per kilometre for the owner-operator if they were to run an EV instead of an ICE. Details of calculations can be found in Appendices.

be as high as 90% [12,13]. These second-hand vehicles are reported to have poor safety and environmental standards [3]. In light of these considerations, to foster the transition to EVs, the price must be acceptable to the owner-operators, close to that of pre-owned Internal Combustion Engine (ICE) vehicles.

Thirdly, the power system is unreliable and insufficient in many countries in SSA [14]. For example, in Sierra Leone there were 53 unplanned blackouts per day throughout 2017.¹ Even in South Africa, one of the more affluent countries in SSA, rolling blackouts are not uncommon [15]. In HICs, the expectation is that power will be available when required; evidently the same cannot be said for countries in SSA. Therefore, it is even more important that the electrification of transport is developed hand-in-hand with the electricity system.

None of the above rule out EVs in SSA, but they do explain the historically low uptake of EVs in this region [4] and highlight the need for innovative approaches, developed with the context in mind. In fact, we propose that if introduced appropriately, EVs could offer benefits to SSA beyond the potential for emissions reductions. These benefits could provide a powerful motivation for pathway development.

2. Discussion

2.1. How might EVs be good for SSA?

Assuming that passengers are technology-agnostic provided they get from A to B without inconvenience, we consider the benefits EVs in SSA could offer to three main stakeholder groups: (i) governments, (ii) electricity providers, and (iii) owner-operators.

2.1.1. Governments

The first benefit to governments is the potential for emission reductions. Emission savings can be calculated by considering the national electricity generation mix and the increased efficiency of an EV compared to an ICE (roughly 90% efficient compared to 12–40%) [16]. In Fig. 1(a) we calculate the potential emissions saving from switching from an ICE vehicle to an EV for each country in SSA. As shown in Fig. 1(a), and in work by Knobloch et al. [17], in all SSA countries electrification of transport would reduce emissions immediately considering the current electricity mix. The highest emissions reductions are possible in countries such as Ethiopia, Uganda, the Democratic Republic of the Congo (DRC), and Namibia. However, even in countries where the emissions reductions are not so pronounced (e.g., South Africa, Botswana, and Niger), electrification of transport still offers the advantage that as electricity generation is decarbonised in the future so, simultaneously, is transport [18]. The second benefit EVs can offer is

improved air quality, especially in urban areas. In SSA, transport attributable particulate matter and ozone were responsible for nearly 4500 deaths in 2015 [19]. Improved air quality results in a positive effect on population health [1], along with the associated economic benefits from, for example, reduced health care spending and fewer lost working days [20]. Another benefit of EV adoption is directly economic. Many governments in SSA provide drastic fossil fuel subsidies, which can be a drain on financial resources. For example, in Botswana and South Africa the 2017 petroleum subsidies were US\$135 and US\$194 per capita, respectively [21]. Fig. 1(b) shows the post-tax government spending on fossil fuel petroleum subsidies per person according to the International Monetary Fund. Subsidies distort the market and can result in increased consumption of fossil fuels. By converting to EVs, money could be diverted from fossil fuel subsidies to financing cheap, clean electricity generation and fossil fuel consumption could be reduced. Often these subsidies are adopted to avoid fuel poverty, which must be considered in any subsidy reform. In countries that also employ fuel taxes alongside subsidies, for example Ethiopia [22], reduced fossil fuel consumption will result in reduced tax income, which may need to be recovered by other means. However, some advantages to reduced fossil fuel consumption still exist in these contexts. A reduction in fossil fuel imports can both increase geopolitical independence and reduce the strain on a government's often limited foreign currency [23]. Of course, for the small number of countries in SSA that produce oil – such as Nigeria and Angola [24] – the benefits may be more questionable, but this will be the case for any motion to depart from a fossil-dependent economy.

2.1.2. Electricity providers

The main benefit of EV uptake for electricity providers is increased revenue. In SSA the electricity providers are often Independent Power Producers or state-owned utilities, many of which are struggling [25]. EVs will create increased energy demand and essentially act as an anchor load which boosts revenue to providers. If half of the road transport were electrified, this would create a demand of 200 TWh per annum across SSA, a market which could equate to US\$14 billion under current pricing (calculation in appendices). To meet this demand, additional clean energy capacity will likely be necessary (e.g., from solar photovoltaics (PV)) [26]. The profits earned could be re-invested to increase clean generation capacity or improve electricity systems overall. Additionally, EVs could offer an opportunity to improve grid reliability through Vehicle-to-Grid (V2G) or Vehicle-to-Home (V2H). By using the battery within the EV as an energy storage asset, which can inject electricity back into the grid, house or building in times of need, thus improving electricity reliability [27]. This is especially relevant as the capacity of renewable energy generation increases.

2.1.3. Owner-operators

We consider there to be two main benefits of EV adoption for

¹ Based on blackout data from Sierra Leone's Electricity Distribution and Supply Authority.

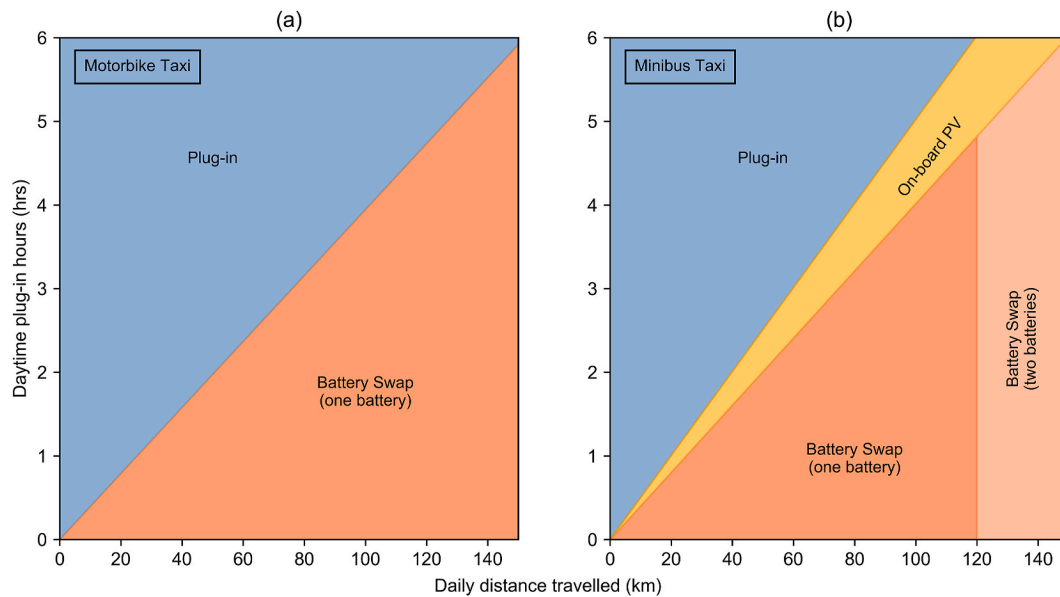


Fig. 2. Look-up figure to identify most suitable EV charging technology for (a) motorbikes and (b) minibuses given daily distance travelled and the daylight plug-in hours, based on indicative values.

paratransit owner-operators resulting from the development of SSA specific EVs: (i) cheaper operating costs, and (ii) lower vehicle capital costs compared to EVs designed for HICs.

Firstly, lower operating costs compared to ICE vehicles are possible due to more efficient vehicle drivetrains and the difference between the price of electricity and vehicle fuel. The cost savings are shown in Fig. 1 (c) for various SSA countries. In all SSA countries (except Liberia), it is cheaper per kilometre to operate an EV instead of an ICE, resulting in reduced total cost of ownership. In some cases, such as the DRC and Zambia, cost savings are over US\$0.15/km. Annually, in these countries, this can translate to a cost saving of US\$3900 per vehicle, see [appendices](#) for details. If fuel subsidies were removed, the saving per kilometre for an EV compared to an ICE would increase even further.

Secondly, currently, for many owner-operators a new vehicle is unaffordable [28]. The vehicle capital cost is considered a key barrier to uptake. Therefore, to lower vehicle capital cost, affordable vehicles must be designed and manufactured. This could be achieved through local manufacturing of SSA specific EVs, such as the e-motorbikes manufactured by Ampersand in Rwanda and the e-buses being built in Uganda [29]. Alternatively, retrofitting vehicles to be electric could lower prices even further and could be a more widely achievable option. Innovative financing or leasing could also help to lower the burden of capital cost of vehicle ownership.

Although these benefits may provide significant motivation for EV adoption, challenges remain, not least surrounding how these vehicles would charge.

2.2. The elephant in the room: EV charging

As discussed, electricity systems in SSA are notoriously unreliable. Additionally, distribution networks are often constrained in their technical capacity. At first glance, the prospect of adding an additional load in the form of EV charging may appear at best daunting or at worst foolish. This is further complicated because not all locations suitable for EV charging currently have access to the electricity grid.

However, the electricity generation mix is transitioning to incorporate greater renewable capacity. With the falling cost of renewable energy, and climate change commitments as part of the Paris Agreement, SSA countries are shifting from centralised fossil-fuelled power plants towards clean renewable generation, exploiting their abundant natural

resources. For example, Kenya now has over 820 MW of geothermal capacity [30] and is home to the largest wind farm in Africa which is over 300 MW [31]. In 2018, US\$2.8 billion were invested into renewables in SSA (excluding South Africa). As part of this an additional 440 MW of PV capacity was installed [31]. In other countries, such as South Africa, Ethiopia, and Tanzania, PV generation shows significant potential in the range of 8–37 GW [32]. Co-locating PV with EV charging not only provides additional generation to meet this new demand, but also eases constraints on local distribution networks and mitigates the need to reinforce the network.

For those installing generation, the aim is always to maximise the units of electricity sold. Novel, context-specific EV solutions may provide an answer to this. For instance, EV charging could be coordinated with times of surplus generation to “soak-up” any excess energy. This “smart charging” has been shown to reduce requirements for additional generation capacity and network reinforcements [33]. In comparison, uncontrolled charging, which is when vehicles charge at full power as soon as they plug in, could double peak power demand as was found in a Kenyan case study [34].

However, one cannot assume that vehicles are available for charging at all times. Local mobility patterns must be taken into consideration when determining the most appropriate technical option. For example, unlike private cars in HICs, which are parked 95% of the time, paratransit vehicles in SSA have a higher usage to provide mobility services. Technical solutions that are appropriate to the application must be selected.

2.3. Technology choices to enable EV integration

To identify the most appropriate EV charging options, we present a deep dive into two of the aforementioned paratransit vehicles – the minibus taxi and the motorbike taxi – and three EV charging technologies: battery swap, plug-in charging, and on-board PV, each described below. We will consider the suitability of said technologies under different usage scenarios, when electricity for charging is provided by co-located PV. In other words, the batteries must charge during daylight hours.

Battery swap requires vehicles to be designed so that the battery can be removed and replaced with a fully charged battery within minutes [35]. This allows the battery to be charged whenever there is excess

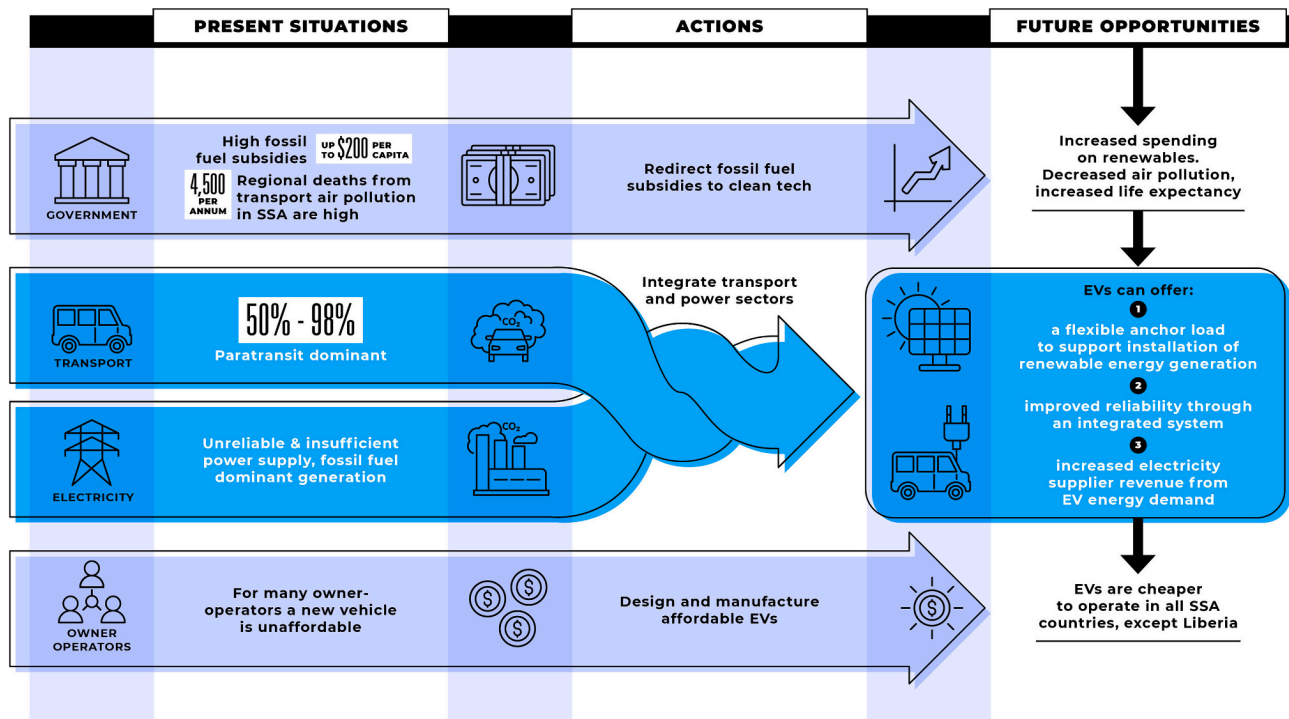


Fig. 3. Schematic to show the future opportunities offered by electric vehicles in the paratransit sector in SSA, and the actions necessary to transition to this future from the present situation.

power generation and at times when the vehicle is not stationary, minimising generation curtailment. For example, battery swap could allow vehicles that are used during the day to swap their batteries that evening for a twin battery which has been outside the vehicle, using solar PV to charge during the day. The pattern then repeats the next day. In this way, battery swap decouples charging from driving patterns, which can be advantageous to vehicles that do not spend much time parked. The challenges are that a vehicle must be specifically designed to allow this, multiple batteries are needed per vehicle, and a suitable battery swap station network is required. All of these can be expensive and the battery swap business model has been seen to fail for cars in some HICs in the past (e.g., Better Place in 2013 [36]). However, in Taiwan, this model has been especially successful for motorbikes in recent years, with the company Gogoro now expanding its business model to India [37].

Plug-in charging, in this work, refers to vehicles which are plugged in and charge from stationary solar PV. Therefore, the vehicles must be parked at a charging point for sufficient time during the day in order to charge. It is assumed that the solar PV is installed at a capacity able to meet the EV demand during hours of generation. Solar PV covered EV parking bays offer a clean charging solution at the same time as providing shade [26]. The challenge is that the vehicle must be out-of-use and plugged in for sufficient daylight hours to charge. This needs to be carefully considered in conjunction with vehicle operating hours to make sure charging does not interfere with mobility service offerings. For many minibuses this may work well as they operate predominantly during commuter-hours and can be stationary during the middle of the day.

On-board solar is when solar PV is placed on the body of the vehicle. This is best suited to minibuses which have a larger body area, and this, therefore, is not considered for motorbikes in this work. The presence of PV on the vehicle body allows the vehicle to charge wherever it is during the day, whether it is parked or in motion. This reduces the energy demand of the vehicle when it is plugged in and reduces the number of daylight hours during which the vehicle must be parked and charging [38]. This technology is not currently widely available, but there is

active research and development in the area with the Fraunhofer Institute recently commencing project 'Lade-PV' which integrates light-weight PV into commercial good vehicles [39]. However, the addition of PV on the rooftop adds an expense and additional weight to the vehicle. It is also vulnerable to vandalism and crime due to the valuable PV panels [40].

Fig. 2 is a look-up figure to demonstrate the conditions under which each technology is suitable for (a) motorbike taxis and (b) minibus taxis. Separate figures for the two modalities are necessary due to different energy consumption per kilometre (kWh/km) and different charging powers: 3.5 kW for a motorbike and 11 kW for a minibus. Further details can be found in the [appendices](#).

The figure shows that vehicles which travel longer distances each day, and do not have sufficient time plugged in during daylight hours, may benefit from the adoption of a battery swap model. In some circumstances minibuses with on-board PV may benefit from a slight reduction in plug-in hours for charging. To understand the financial implications, for minibuses, on-board PV appears to be favourable when compared with a battery swap system, based on a calculation assuming a 2 kW PV array which costs US\$2600 [41], compared to an additional 60 kWh battery pack which costs US\$9360 [42]. However, sufficient space is necessary on the vehicle.

From this example, it is clear that there is no silver bullet. Technology choice depends significantly on driving patterns, and until mobility patterns are well recorded, it is challenging to determine which technology will be most suitable. This results in challenges for EV charging infrastructure planning and efforts must be made to gather and make available the required data [6].

3. Conclusion

In conclusion, we challenge the perception that EVs in SSA are an optimist's fantasy. Despite the obvious barriers of an unreliable electricity system and a lack of capital, we argue that EVs could offer benefits to governments, electricity systems, and paratransit owner-operators. The key to realising these benefits is to design EV systems

which are context-specific and differ from existing HIC approaches.

If this is achieved, the majority of EVs in SSA will not take the form of the HIC private car. Instead, they will correspond to the modes of transport common in SSA such as the minibus or motorbike. Moreover, the vehicles and their charging infrastructure will be designed to support the marriage of the two previously siloed sectors: electricity and transport. This Viewpoint has highlighted how EVs could be good for SSA, providing benefits such as vehicle emission reductions of over 90%, decreased petroleum subsidies which are currently nearly US\$200 per capita in South Africa, a flexible load to support the electricity network which could be worth up to US\$14 billion in revenue per annum, cheaper vehicle operating costs of up to US\$0.15 per kilometre, as well as a potential route to clean generation investment. These are summarised in Fig. 3.

All of these benefits hinge on understanding SSA transport and electricity systems in their own right, and not shoehorning inappropriate HIC solutions into SSA systems. Context-appropriate technologies and their associated business models need to be developed, be it for new EVs or retrofit options, such as battery swap, plug-in charging with co-located PV, and on-board PV.

Declaration of competing interest

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

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Appendices.

A. Maps

The maps in Fig. 1 were generated using the existing electricity fuel mix in each country in 2019 [43], alongside standard emissions intensity values for each fuel [44]. Vehicle efficiencies of 0.31 kWh/km [45] and 20 mpg [46] were used, which are representative of older inefficient vehicles. A 90% EV charging efficiency was assumed, similar to those observed in home charging points [47].

B. Estimated electricity providers revenue potential

Estimated electricity providers revenue potential is calculated considering that transport demands 69 Mtoe per annum in SSA, equivalent to 800 TWh of energy per annum and that non-road transport is extremely low [2]. As EVs can be up to four times more efficient than an ICE, a transition of all vehicles to electric could result in a transport related electricity demand of 200 TWh per annum. Given that the average electricity price in SSA is US\$0.14/kWh, this equates to a market value of up to US\$28 billion. As a complete transition is extremely unlikely in the near future, we present the value for half the vehicles electrifying, equating to US\$14 billion.

C. Owner-operator annual cost saving

The owner-operator annual cost saving is calculated using a saving of US\$0.15/km, from Fig. 1(c) and assuming the vehicle covers 100 km/day, five days a week, which is reflective of paratransit vehicle

operation.

D. Look-up figure

The look-up figures in Fig. 2 were generated using the following assumptions. Energy consumption was taken to be 0.12 kWh/km for boda-bodas and 0.50 kWh/km for minibus taxis [34]. Battery capacities of the boda-boda and minibus were 20 kWh and 60 kWh, respectively [34]. The charging powers were taken to be the standard 3.5 kW for a boda-boda and 11 kW for a minibus (which is conservative, so as to minimise negative impact on the power network). The onboard solar PV was assumed to extend the vehicle range by 20%, instead of the 31% quoted by Kim et al. [38].

References

- [1] SLoCaT, Transport and Climate Change Global Status Report 2018, 2018.
- [2] International Energy Agency (IEA), Africa Energy Outlook, 2019. www.iea.org/reports/africa-energy-outlook-2019.
- [3] United Nations Environment Programme (UNEP), Used Vehicles and the Environment. A Global Overview of Used Light Duty Vehicles: Flow, Scale and Regulation, 2020.
- [4] IEA, Global EV Outlook, 2020.
- [5] G. Falchetta, M. Noussan, A.T. Hammad, Comparing paratransit in seven major African cities: an accessibility and network analysis, *J. Transport Geogr.* 94 (2021) 103131, <https://doi.org/10.1016/j.jtrangeo.2021.103131>.
- [6] K.A. Collett, S.A. Hirmer, Data needed to decarbonize paratransit in Sub-Saharan Africa, *Nat. Sustain.* (2021), <https://doi.org/10.1038/s41893-021-00721-7>.
- [7] V. Boutueil, G. Lesteven, L. Nemett, Toward the integration of paratransit in transportation planning in African cities, *Transport. Res. Rec.* 2674 (2020) 995–1004, <https://doi.org/10.1177/0361198120933270>.
- [8] I. Ndiabata, J. Coetzee, M.J. Booyen, Mapping the informal public transport network in kampala with smartphones: making sense of an organically evolved chaotic system in an emerging city in sub-saharan Africa, in: *Proc. 35th South. African Transp. Conf. (SATC 2016)*, 2016, pp. 327–337.
- [9] M.J. Booyen, S.J. Andersen, A.S. Zeeman, Informal public transport in sub-saharan Africa as a vessel for novel intelligent transport systems, *IEEE Conf. Intell. Transp. Syst. Proceedings, ITSC.* (2013) 767–772.
- [10] G. Jennings, R. Behrens, The Case for Investing in Paratransit: Strategies for Regulation and Reform, 2017.
- [11] UK Department for Transport, Transport Statistics, Great Britain, 2019.
- [12] T. Schiller, K. Pillay, Navigating the African Automotive Sector: Ethiopia, Kenya and Nigeria, 2016.
- [13] A. Baskin, Africa used vehicle report, in: *African Clean Mobil, Week*, 2018.
- [14] J. Ayaburi, M. Bazilian, J. Kincer, T. Moss, Measuring “Reasonably Reliable” access to electricity services, *Electr. J.* 33 (2020) 106828, <https://doi.org/10.1016/j.tej.2020.106828>.
- [15] M.J. Booyen, J.A. Samuels, S.S. Grobbelaar, LED there be light: the impact of replacing lights at schools in South Africa, *Energy Build.* 235 (2021) 110736, <https://doi.org/10.1016/j.enbuild.2021.110736>.
- [16] J. Martins, F.P. Brito, D. Pedrosa, V. Monteiro, L. Joao, Real-life comparison between diesel and electric car energy consumption, grid electrified veh. Performance, des, Environ. Impacts (2013) 209–232. https://www.novapublishers.com/catalog/product_info.php?products_id=44945.
- [17] F. Knobloch, S. V. Hanssen, A. Lam, H. Pollitt, P. Salas, U. Chewprecha, M.A. J. Huijbregts, J. Mercure, Net emission reductions from electric cars and heat pumps in 59 world regions over time, *Nat. Sustain.* 3 (2020) 437–447, <https://doi.org/10.1038/s41893-020-0488-7>.
- [18] R.T. Doucette, M.D. McCulloch, Modeling the CO2 emissions from battery electric vehicles given the power generation mixes of different countries, *Energy Pol.* 39 (2011) 803–811, <https://doi.org/10.1016/j.enpol.2010.10.054>.
- [19] S. Anenberg, J. Miller, D. Henze, R. Minjares, A Global Snapshot of the Air Pollution-Related Health Impacts of Transportation Sector Emissions in 2010 and 2015, 2019. https://www.theicct.org/sites/default/files/publications/Global_health_impacts_transport_emissions_2010-2015_20190226.pdf.
- [20] OECD, The Economic Consequences of Air Pollution, 2016.
- [21] International Monetary Fund (IMF), IMF Country-Level Subsidy Estimates Database, 2018.
- [22] D. Coady, I. Parry, N.-P. Le, B. Shang, IMF Global Fossil Fuel Subsidies Remain Large: an Update Based on Country-Level Estimates, 2019, <https://doi.org/10.5089/97814834393178.001>.
- [23] International Monetary Fund (IMF), Sub-Saharan Africa: Domestic Revenue Mobilization and Private Investment, 2018, pp. 1–126.
- [24] EIA, EIA, Data: International Primary Energy Production, 2018. <https://www.eia.gov/international/data/world/total-energy/total-energy-production>.
- [25] R. Shirley, B. Attia, Unlocking Utilities of the Future in Sub-Saharan Africa, 2020, <https://doi.org/10.2139/ssrn.3634041>.
- [26] K.M. Buresh, M.D. Apperley, M.J. Booyen, Three shades of green : perspectives on at-work charging of electric vehicles using photovoltaic carports, *Energy Sustain. Dev.* 57 (2020) 132–140, <https://doi.org/10.1016/j.esd.2020.05.007>.

- [27] M. McPherson, M. Ismail, D. Hoornweg, M. Metcalfe, Planning for variable renewable energy and electric vehicle integration under varying degrees of decentralization: a case study in Lusaka, Zambia, *Energy* 151 (2018) 332–346, <https://doi.org/10.1016/j.energy.2018.03.073>.
- [28] M. Adhikari, L.P. Ghimire, Y. Kim, P. Aryal, S.B. Khadka, Identification and analysis of barriers against electric vehicle use, *Sustainability* 12 (2020) 1–20, <https://doi.org/10.3390/SU12124850>.
- [29] J. Gaventa, Africa's Bumpy Road to an EV Future, *Energy Monit.*, 2021. <https://energymonitor.ai/sector/transport/africas-bumpy-road-to-an-electric-vehicle-future>.
- [30] IRENA, *Geothermal Development in Eastern Africa: Recommendations for Power and Direct Use*, 2020. Abu Dhabi.
- [31] Bloomberg New Energy Finance (BNEF), *Sub-Saharan Africa Market Outlook 2020*, 2020.
- [32] IRENA, *Planning and Prospects for Renewable Power: Eastern and Southern Africa*, Publication forthcoming, 2021.
- [33] C. Crozier, T. Morstyn, M. McCulloch, The opportunity for smart charging to mitigate the impact of electric vehicles on transmission and distribution systems, *Appl. Energy* 268 (2020), <https://doi.org/10.1016/j.apenergy.2020.114973>.
- [34] K.A. Collett, M. Byamukama, C. Crozier, M. McCulloch, *Energy and Transport in Africa and South Asia*, 2020.
- [35] H.Y. Mak, Y. Rong, Z.J.M. Shen, Infrastructure planning for electric vehicles with battery swapping, *Manag. Sci.* 59 (2013) 1557–1575, <https://doi.org/10.1287/mnsc.1120.1672>.
- [36] E. Niesten, F. Alkemade, How is value created and captured in smart grids? A review of the literature and an analysis of pilot projects, *Renew. Sustain. Energy Rev.* (2016).
- [37] S. O'Kane, Gogoro Is Bringing its Electric Scooter and Battery Tech to India, *The Verge*, 2021. <https://www.theverge.com/2021/4/21/22394575/gogoro-india-hero-motorcorp-electric-scooters-battery-swap-stations>.
- [38] J. Kim, D. Baek, J. Hong, N. Chang, Partially solar powered full electric vehicles, *Midwest Symp. Circuits Syst* (2014) 358–361.
- [39] I.S.E. Fraunhofer, *Lade-PV Project Begins: Vehicle-Integrated PV for Electrical Commercial Vehicles*, 2020, pp. 6–8.
- [40] E.C.X. Ikejamba, P.C. Schuur, Analyzing the impact of theft and vandalism in relation to the sustainability of renewable energy development projects in Sub-Saharan Africa, *Sustainability* 10 (2018) 1–17, <https://doi.org/10.3390/su10030814>.
- [41] International Energy Agency (IEA), *Capital Costs of Utility-Scale Solar PV in Selected Emerging Economies*, 2020. <https://www.iea.org/data-and-statistics/charts/capital-costs-of-utility-scale-solar-pv-in-selected-emerging-economies>.
- [42] Bloomberg New Energy Finance (BNEF), *Electric Vehicle Outlook 2020*, 2020.
- [43] International Energy Agency (IEA), *Electricity Generation by Source*, 2019.
- [44] V. Krey, O. Masera, G. Blanford, T. Bruckner, R. Cooke, K. Fish-Vanden, H. Haberl, E. Hertwich, E. Kriegler, D. Müller, S. Paltsev, L. Price, S. Schlömer, D. Uerge-Vorsatz, D. Van Vuuren, T. Zwickel, Annex II: metrics & methodology, in: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Annex II.9.3 Lifecycle Greenhouse Gas Emissions, 2014. http://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_annex-ii.pdf.
- [45] C. Crozier, PhD. Thesis, *The Impact of Domestic Electric Vehicle Charging on Electricity Networks*, University of Oxford, 2020.
- [46] I. Parry, D. Heine, S. Li, E. Lis, *IMF Getting Energy Prices Right: from Principle to Practice*, 2014. www.imf.org/environment.
- [47] J. Sears, D. Roberts, K. Glitman, A comparison of electric vehicle level 1 and level 2 charging efficiency, in: *2014 IEEE Conf. Technol. Sustain.*, 2014, pp. 255–258. IEEE.