Energy and transport in Africa and South Asia

State of knowledge paper

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Abstract

In Africa and South Asia, the transition to low-carbon vehicles is vital in mitigating climate change. There will be socio-economic co-benefits associated with reduced dependence on oil imports, cleaner air in cities, and lower running costs, negating the need for energy subsidies. This report identifies that the most suitable low-carbon alternative is the introduction of electric vehicles. Pathways to deliver electrification in Africa and South Asia are discussed and the impacts on the power network are considered. The key knowledge gaps are identified as: (i) the number of vehicles in each modality in each country, which can be addressed by vehicle registration and open-data policies; (ii) the driving patterns of the different modalities, which encompasses consumer use of transport and will be used to identify modalities with the most promising value proposition and therefore most likely uptake; (iii) a detailed cost-benefit analysis of the different pathways to electric mobility (retrofit or purchase), which should be accompanied by government-level analysis to set out country-specific appropriate pathways and identifying policy to support these; (iv) an in-depth analysis of the impact on the power network, to inform policy around additional clean energy generation and distribution network upgrade; and (v) a country-specific business cases for mechanisms to reduce the impact on the power network (battery swap or smart charging). Policy and regulatory questions surrounding electric vehicle registration, battery supply chain and end-of-life, and redistribution of fuel taxation or subsidies are highlighted.

1 Introduction

To mitigate climate change, it is vital that global transport is decarbonised. In Low- and Middle-Income Countries (LMICs), such as those in Africa, road transport is often the most dominant mode of motorised transport–in Africa accounting for 80% of cargo and 90% of passenger traffic.[1] In 2014, the CO_2 emissions from road transport in Sub-Saharan Africa were almost 0.2 Gt of CO_2,[2,3] and in India transport emissions were similar at 0.27 Gt of CO_2.[4] Combined, this already accounts for over 1% of global CO_2 emissions.[3] With rapid urbanisation, economic growth, and the population expected to grow exponentially, CO_2 emissions from transport could grow substantially. For example, in the US, CO_2 emissions from transport are currently circa 5.5 tons per capita.[2,3] If urbanisation and economic growth enabled African mobility per capita growth to be even half of this, CO_2 emissions for the combined African population of 1 billion[5] could be as high as 3 Gt, a 15-fold increase. This is without considering population growth, which is expected to result in the population of Africa more than doubling, to over 2 billion, by 2040.[6] Thus, decarbonising road transport in Africa and South Asia is vital in mitigating climate change as it could prevent significant CO_2 emissions. It may also improve local urban air quality, which is becoming an increasing concern.[7]

On top of this, decarbonising transport will provide economic benefit. Over half of all African countries subsidise fuel to protect consumers from the high costs.[8] By reducing country dependence on imported fossil fuels, political and economic advantages should be realised. India has already ceased diesel subsidies in a government-led backing of vehicle electrification.

After having considered the three technical options for decarbonising transport (biofuels, fuel cells and electrification), this paper focuses on answering the question: *should Africa and South Asia transition to electric mobility?* It highlights the knowledge gaps that must be filled in order to confidently answer this. There are five important topics to consider: technology, context, pathways, finance, and the power system. Firstly, Section 2 addresses the question whether other low-carbon technologies can compete with electric vehicles (EVs). Secondly, the specific context is split into two sections: Section 3 discusses the evolving modalities of transport in Africa and South Asia, and Section 4 describes the associated opportunities. Thirdly, pathways to electrification of mobility are covered in Section 5. Fourthly, the financial payback time for electrifying vehicles by retrofit is calculated in Section 5. Finally, having considered the need for and viability of creating an EV fleet, the impact on the power system is discussed in Section 6.

2 Low-Carbon Vehicles

The three most promising low-carbon alternative fuels are EVs, biofuel vehicles, and hydrogen vehicles. The winning technology must be price-competitive with internal combustion engines so that it is affordable for consumers (e.g. does not require unobtainable infrastructure investment), and will need to offer the potential of significant fossil carbon emission reductions. It will also need to be capable of achieving consumer acceptance (e.g. not pose perceived safety concerns). All of this can be influenced and supported by policy decisions, but for now the technical aspects of low-carbon transport technologies are considered.

Biofuel has the advantage of being able to utilise the existing petrol distribution network and can be relatively effective (although not entirely effective) in reducing fossil-carbon emissions. This is influenced by the type of feedstock and where it is grown (e.g. does the crop growth lead to deforestation?). However, to run a vehicle on biofuels a different engine is necessary. Additionally, biofuel vehicles require more energy to run than internal combustion engine vehicles, CO_2 is still released at the vehicle tail-pipe (so there is no air pollution advantage), and biofuel crop growth could compete with food crop growth for food. Although biofuel for freight is widespread, it is rarely used for other modalities.

Hydrogen as a transport fuel has potential, but at the moment clean hydrogen production is at an early technology-readiness level and hence is expensive. There are also safety concerns and technical challenges associated with storing hydrogen in a vehicle, which may affect consumer adoption. The use of hydrogen would require the costly development of separate infrastructure; for countries with limited cash, this may be prohibitive. On top of this, there has been substantial global investment into hydrogen fuel cell vehicles, and they are still to reach the mass market.

EVs have three main advantages. Firstly, they have reached the mass market. Secondly, they require a reduced energy consumption compared to petrol vehicles. Thirdly, they have the advantage of utilising the pre-existing electricity distribution network. These result in EVs being the alternative fuel technology most likely to be cost competitive to petrol vehicles. Having considered the above, EVs will be the focus of the remainder of this paper. Additionally, EVs have an efficiency that is higher than biogas vehicles, and comparable to hydrogen vehicles. However, the emissions reduction achieved depends on the fuel mix used to generate the electricity.

For all of these technologies, the fuel could be produced in the country of use, reducing dependence on imports and creating growth potential.

Further details on biofuel and hydrogen vehicles, including a table of existing vehicles, are available in the Appendices. The rest of the report will consider only EVs.

2.1 Electric Vehicles

Battery electric vehicles (sometimes called pure-electric vehicles) do not have internal combustion engines and are powered exclusively by a large battery, which needs to be charged externally. These vehicles are already available to purchase for the majority of transport modality types, as shown in Table 3.

EV chargers can be connected to an existing electricity distribution grid, so users can charge their vehicle at any place where a charger can feasibly be installed. This gives EVs an advantage over alternative fuels because a fuel distribution network likely already exists to some extent.

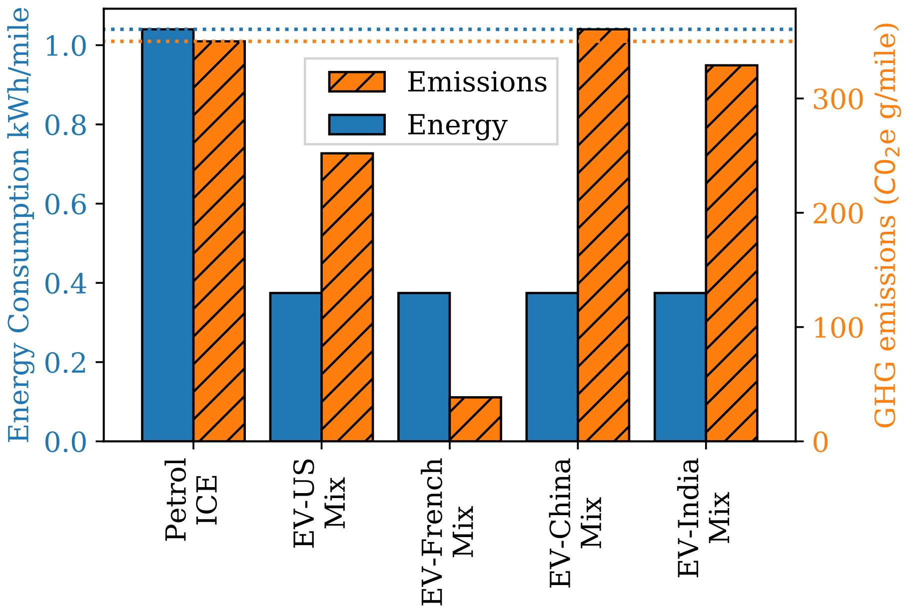

Figure 1: The reduction in emissions and energy consumption achieved with EVs, using the fuel mix from large economies as low- and middle-income countries were not considered.[9]

Figure 1 shows the well-to-wheel energy consumption and emissions of electric vehicles compared to petrol vehicles for the fuel mix of several large-economy countries.[9] The reduction in energy use is the same in each case, but the emissions vary significantly. Using the French mix, which contains a lot of nuclear and hydro, an 88% reduction in emissions is possible. However, the Chinese mix, which is dominated by coal, results in an increase in total emissions. Theoretically, a zero-emissions EV is possible, providing it can be charged exclusively with low-carbon renewable energy.

Overall, EVs currently offer the greatest opportunity for low-carbon transport as they are the only technology which reliably reduces both energy and emissions. However, it should be noted that the emissions reduction achieved depends strongly on the fuel mix used to generate the electricity.

3 African and South Asian Context: Mobility

To assess whether a country or region should transition to EVs, it is important to know what the mobility landscape is like. This is vital in determining the impact on the power network and understanding the attractiveness for investment. This section discusses the vehicles that are commonplace, how they are used, how many there are of them, and where they are used (which relates to urbanisation).

3.1 Transport Modalities

There are two main categories of vehicle ownership: ownership of mobility service vehicles and ownership of private vehicles.

In many Sub-Sahara African countries, the public transport system consists of four tiers — buses, minibuses (see Figure 2), motorcycle-taxis, and sometimes car-taxis. Additionally, in India, rickshaws are extremely popular and are used in the same way as motorcycle-taxis.. Minibuses, buses and motorcycles/rickshaws service the majority of public transport needs. In Uganda for example, these account for nearly half (46%) of the total traffic.[10] While transport by air, rail, and sea is available, road transport makes up 90% of the passenger traffic.[1] Within cities such as Lagos, Nigeria, road transport can account for up to 95% of passenger trips,[11] where 12 million trips are made per day.[12]

Figure 2: Example of a Minibus in South Africa

The majority of private vehicles are bought pre-owned from high income countries. In 2014, Sub-Saharan Africa recorded 2% of vehicle ownership compared with 70% in the United States, 50% in Europe, and 6% in China.[13] Used cars constitute 70%, 84%, 85%, and 96% of vehicles in Ghana, Zambia, Uganda, and Kenya.[13]

Freight is a challenging topic that has yet to be solved by highly developed economies such as the UK and the US. Currently, the technology readiness level is still low. The only credible low-carbon freight option at the moment is biofuel; however, as discussed before, there are still emissions associated with this. Tesla is developing the electric Tesla Semi,[14] and hydrogen fuel cell vehicles are under development.[15] Both of these solutions are likely to be a decade from commercial viability.

Rail has two quite different characteristics in Africa and India. In India, the rail network is heavily utilised and expansive, accommodating 54% of passenger traffic. It is also already predominantly electric, with plans for all routes to be electric by 2022.[16] Therefore, there is little scope for improvement, although electric rail network expansions are planned.[4] In contrast, African rail infrastructure is limited[17] and there would likely be large economic and political hurdles in transitioning to rail transport in Africa. Following this, rail is not considered further.

The common modes of transport in Africa and India are summarised in Table 1 along with indicative values for distance travelled per day.

Mode	Seats	Typical Use	Daily use (km)
Freight	1-3	Intra and inter-town cargo	1-1000
Buses (Coaches)	Over 50	Public national and cross-border	50-1000
Minibus	10-30	Public national and intra-town	100-500
Private cars	4-14	Private transportation	0-500
Auto-rickshaws	1-3	Intra and inter-town transportation	5-100
Motorcycles	1-3	Intra-town transportation	5-100

Table 1: An overview of the transport modalities commonplace in Africa and India with indicative values of daily driving distances

According to Table 1, the passenger vehicles that travel the greatest distance per day are the buses and minibuses, followed by the rickshaws and motorcycles. These are also the modalities that have the highest passenger capacity. This means that electrifying these modalities will have the greatest impact on decarbonising passenger journeys. However, the impact will also depend on the number of vehicles on the road for each modality.

Five countries (South Africa, Uganda, Nigeria, Egypt, and India) were selected to represent Africa and South Asia. The number of vehicles for each transport modality was gathered for each country and are shown in Table 2.

Mode	Nigeria[b]	Uganda[c]	South Africa[18]	Egypt[19]	India[20]
Freight vehicles	*	*	2.7 M	*	9.2 M
Buses (Coaches)	*	*	57,000	140,000	2.1 M
Minibus	*	20,000-25,000	294,000	*	See note[e]
Private cars	4.7 M	*	6.6 M	4.3 M	28.6 M
Auto-rickshaws	> 40,000[a]	*	370,000	100,000	> 1.5 M See note[e]
Motorcycles	8 M	120,000		3 M	154 M
TOTALS	19.6 M	640,000	10.2 M[d]	9.3 M	210 M[e]

* No available data

[a] Just in Aba metropolis in Nigeria

[b] The Nigeria Bureau of Statistics[21] puts the current population of vehicles at 11.6 million, of which 6.7 million are commercial vehicles (58%); private cars are about 4.7 million (41%). This number does not include commercial motorcycle taxis, believed to be about 8 million in number.[22]

[c] In Uganda, the total number of licensed vehicles is over 630,000 according to the Uganda Revenue Authority and an average of 42,000 cars and 85,000 motorcycles are registered each year.[23] Minibuses and motorcycle taxis are the most popular public means of transport. Although there are about 17,000 registered 14-seater minibuses, Kamuhanda and Schmidt[10] suggest that the actual count is greater since considerable numbers of these are operating unregistered.

[d] In South Africa, 230,000 vehicles are classified as “other”. Data from 2014.

[e] India classifies 15.8 million vehicles as “other”. These are likely to include auto-rickshaws and minibuses. There are reports that there are already over 1.5 million e-Rickshaws on the roads in India.[24]

Table 2: Composition of transport modalities available in four selected African countries and India

There are many blank entries in Table 2 for which data were unavailable. This was also the case in Table 1, where large ranges were used for the average distance travelled per day to account for the fact that data were unavailable. This is the first knowledge gap to highlight. Until the number of vehicles and the journey routines are understood more clearly, it will be challenging to be precise in stating the impact that electrification would have on the power network and develop relevant policy. Both the distance travelled and the time at which the vehicle is parked have a profound impact. Therefore, the number of trips and the idle time of the vehicles are valuable information.

3.2 Currently Available Electric Vehicles

The currently available EVs for the above-mentioned transport modalities are summarised in Table 3.

Mode	Available Electric Vehicles
Freight	**Development**: Asia[25] growth expected,[26] USA[14]
Buses	**Mass market**: China,[25,27–29] **New entrant**: Europe,[27] USA[30–32] growth expected[26]
Minibus	**Purchase possible**: USA (Nissan[33]) **Prototype**: Mercedes-Benz[34] **Under development**: VW,[35] Chrysler,[36] Toyota[37]
Private cars	**Mass market**: China, Europe, USA, Japan[38–40]
Auto-rickshaws	**Mass market**: India[24] (inc. battery swap schemes)[41–43]
Motorcycles	**Mass market**: China[29,44]

Table 3: Electric vehicle status in 2019 by transport modality

For all modalities it is possible to purchase an EV of that type somewhere globally. This does not mean that these vehicles would be affordable in the African and South Asian markets, where the vast majority of vehicles are purchased pre-owned. However, it demonstrates the application of electric drive-trains to a range of transport modalities.

3.3 Urbanisation and its effects

In Sub-Saharan Africa, only 40% of people currently live in Urban areas and in India only 34%[45] (in contrast to 83% of people in the UK or the US).[45,46] However, urbanisation in Africa is happening fast. In 2018, the average urban population growth in Sub-Saharan Africa was 4.1%,[47] compared to India, where the rate is 2.3%, and globally, where the average is 1.9%.[47] Some countries, such as Uganda, Burundi, Ethiopia, and Mali, have particularly high rates of 4.8–6.2%.[47,48] This rapid urbanisation offers several opportunities for transport-related decarbonisation.

Firstly, urbanisation is often correlated with increased GDP[49] and thus the potential for increased spending on mobility, as shown in Figure 3. Sub-Saharan Africa relies almost entirely on fossil fuels for road transport. The same is true of India, although there is recent policy in place and subsidies to change this trajectory and encourage uptake of EVs. This correlation means that, at present, carbon emissions from road transport are a good indicator of transport use. Figure 3 shows the CO_2 emissions from transport against GDP per capita for various African countries. The population size and petrol price is also represented. This figure demonstrates a correlation between GDP and emissions from transport. As GDP increases, more is spent on transport. The implication is that the use of transport is likely to increase with urbanisation. As EV-related savings are due to a per-kilometre fuel saving (to be discussed in Section 5), this could result in reduced payback times, thus encouraging investment in the EV sector.

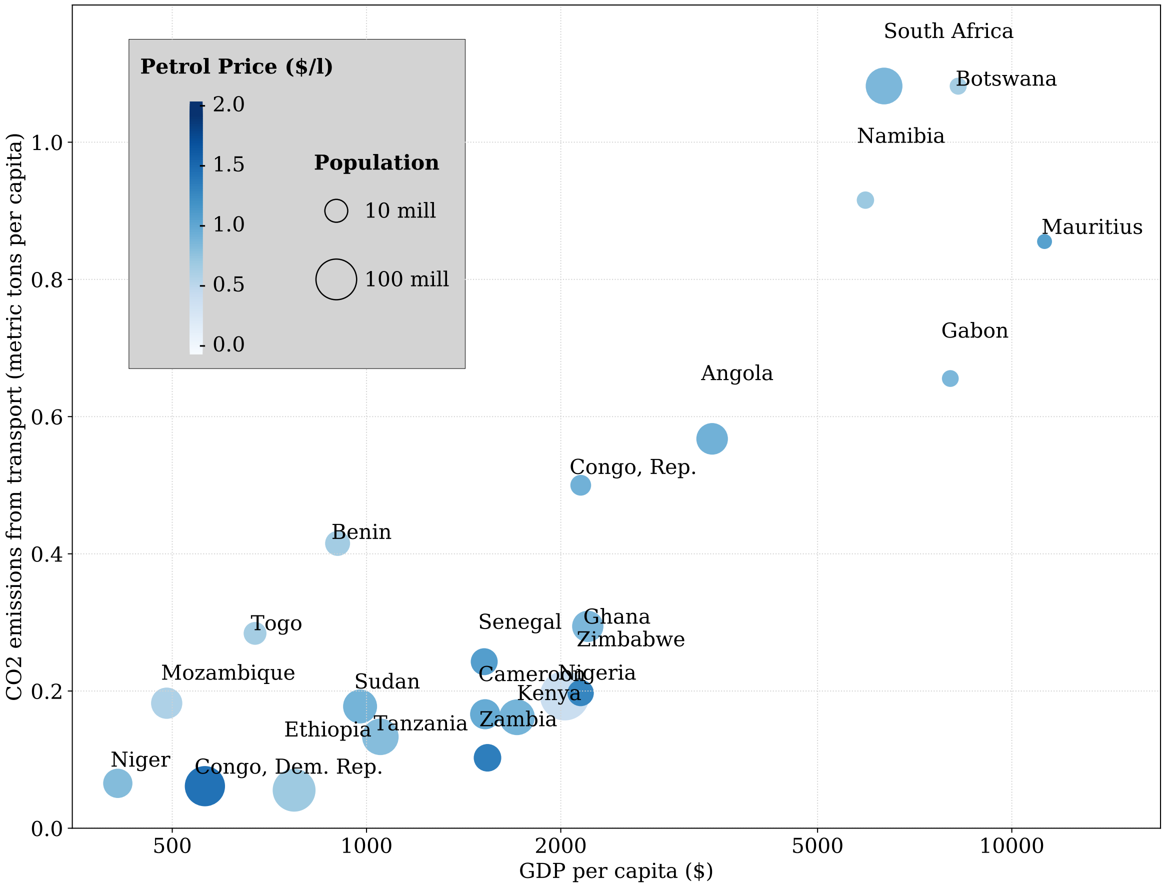

Figure 3: CO_2 emissions[2,3] against GDP per capita[50] for a range of African countries. Population size[5] and petrol cost[51] for 2018 represented as in the legend.

Secondly, urbanisation will result in concentrated demand, with the need for EV charging points and supporting infrastructure predominantly being situated in the towns and cities. This reduces the need for geographically widespread network reinforcement, thereby limiting the cost.

Thirdly, the demand for electricity in India and Africa is growing, as well as in Sub-Saharan Africa, and may increase by a factor of 4 by 2040.[52] More countries are looking to low-cost renewable generation using solar, hydro, and wind to grow capacity. Countries like Kenya have over 70% of their electric power demand supplied by renewable sources[53] and aim to reach 100% by 2030. The overarching challenge is that these sources are intermittent.[54] However, EVs can offer a complimentary asset to this as flexible demand. In the future, EV batteries could even act as energy storage, able to discharge in order to the satisfy local demand in times of low generation. This is a concept known as vehicle-to-grid (V2G),[55] which is discussed further in the Appendices.

An important result of urbanisation will be the increased need for intra-city transport, making minibuses and motorcycles two of the most promising modes of transport to target for initial electrification. These vehicles, which provide mobility as a service, are often clustered around transport hubs, which may offer further advantage for electrification as demand for charge points and network reinforcement (e.g. local low-cost generation) is focused.

4 African and South Asian Context: Opportunities from Electric Vehicles

There exist socio-economic, technical, and regulatory opportunities and challenges that will influence the penetration of EVs in Africa and South Asia. These are summarised below and will be considered in determining suitable pathways to electrification, discussed in the next section.

The opportunities are as follows:

- Excess generation: some countries generate more electricity than they consume and therefore have a net export, which is shown in Figure 4. This excess generation could be directed to strategic hubs for flexible EV charging.

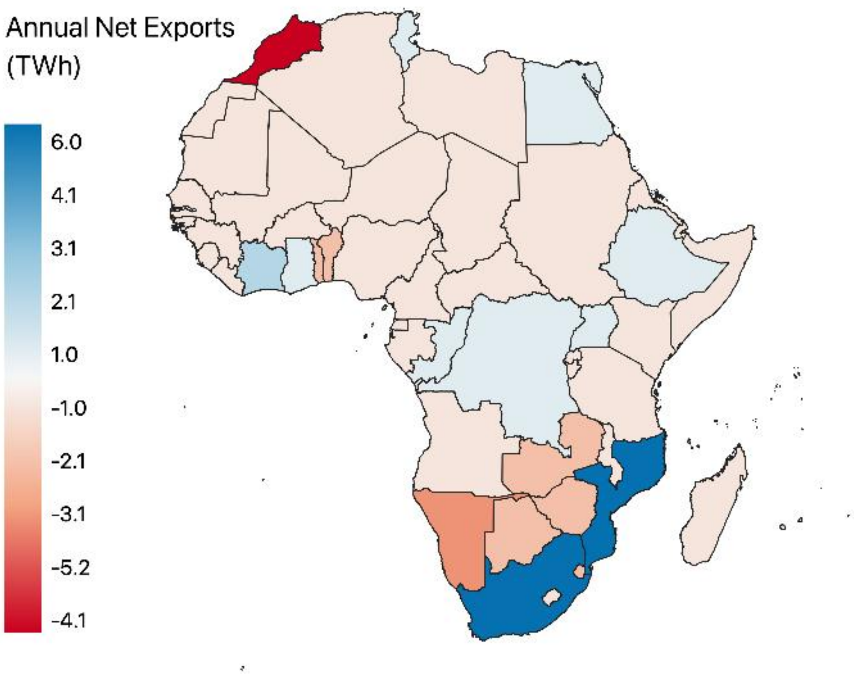

Figure 4: Annual net electricity export for African countries[56]

- Geographical location which favours zero carbon generation: Africa and South Asia are well situated to harness low-cost, renewable energy generated from solar, wind, hydro, and geothermal sources.

- E-mobility friendly governments: some governments in Africa have expressed an explicit commitment to adopt electric mobility. Since 2017, Morocco has stopped imposing customs duties on imported EVs.[57] The Rwandan government has introduced a national e-mobility policy citing air pollution in the transportation sector as the driver, and companies like Ampersand are now set to manufacture 3 million electric motorcycles for the East African market.[58] Companies like BMW and Nissan Leaf are running operations that have sold over 1000 units in South Africa since 2013.[59] Kenya has seen increasing imports of EVs since 2016 for use as taxis from the Finnish company EkoRent and is expected to have a fleet of over 150 EVs by mid-2020 and 1500 units by end of 2021.[60] India has pledged to reach 100% EV sales by 2030 and there is \$ 1.4 billion available for electric and hybrid vehicle subsidies.[4]

Figure 5: Photo of parking bays covered with solar PV generation in Johannesburg, South Africa

- Vehicle Range: EV battery range is dependent on ambient temperature.[61] Warm temperatures offer favourable conditions. Africa and South Asia are frequently within the 20-35°C range. Thus, EVs would benefit from having longer driving ranges.

- Reduced subsidies: over half the African countries subsidise vehicle fuel to protect consumers from the high costs.[8] By reducing country dependence on imported fossil fuels instead relying on domestically produced energy, political and economic advantages should be realised. India has ceased subsidising already.

- Reduced fuel imports will decrease the call on foreign exchange reserves and facilitate geopolitical independence.

- Improved air quality: this is one of the main drivers for countries like Rwanda.[58] As urbanisation continues, this will become more pronounced.

- Increase utility company revenue: EVs create a flexible demand for electricity, which should increase utility company revenue and enable investment into low-cost renewable generation.

- Potential job creation: the emergence of a new market usually results in job creation. The extent of industry and job creation will depend on the chosen pathway to electrification.

The challenges of electrifying transport in Africa and South Asia include the following:

- Limited access to capital: African countries tend to be low- or middle-income, as is India, with limited capital to spend on new vehicles. This is demonstrated by the fact that almost 80% of privately owned vehicles are pre-owned in Africa.[13] This may require third-party asset ownership, or low-cost loans.

- Limited grid expansion in rural areas: there is often poor grid coverage in rural areas because it has not been profitable for private distribution companies. This could change if the introduction of EVs provided a suitable business model for companies to invest in charging infrastructure in rural areas, potentially providing the benefit of increasing energy access at the same time.

- Unreliable power: this is usually caused by a mismatch between demand and generation of (renewable) resources, or poor maintenance of the distribution network. In some countries, this frequent power deficit results in the decision to ration electricity supplied to consumers. According to the World Bank, countries in Sub-Saharan Africa have annual outages ranging from 50 hours to up to 5000 hours,[62] i.e. over 50% of the time in some cases. For countries where this is the case, flexible charging of EVs (i.e. the ability to shift in time when a vehicle charges) will be of paramount importance to facilitating their adoption.
- The carbon intensity of electricity generation can be high: in some countries, such as South Africa, the carbon intensity of electricity may mean that EV adoption is not favourable with regard to fossil carbon emissions, see Figure 6. However, even in such instances, the adoption of EVs has advantages.
  - Firstly, urban air quality may be improved due to the lack of tailpipe CO_2 emissions.
  - Secondly, the use of electricity for mobility provides additional revenue for the power utility companies. This profit could be reinvested to increase the capacity of renewable generation, which could even be co-located with vehicle parking and charging hubs, as in Figure 5.
  - Finally, as a result of the above, it is then possible to decarbonise power generation and mobility at the same time.
- EV registration will need to be possible in all countries wishing to encourage transport decarbonisation and electrification. Regulation to enable this may be necessary.
- Supply of battery materials should be ethically certified, and appropriate end-of-life policies should be implemented to ensure ethical and environmental standards are upheld. The mechanisms to achieve this without prohibitively increasing costs will need to be explored.
- Although fuel is subsidised in many countries, in some, e.g. South Africa, fuel is taxed. Any reduction in the value of fossil fuel consumption will affect this tax revenue, which will likely need to be recovered by some other mechanism enforced by policy.

The opportunities highlight that countries that currently export energy and where governments are committed to decarbonising transport would be appropriate locations for initial electrification trials. For example, the retrofit of at least two proof-of-concept minibuses might be trialled with customers for 6 months in South Africa.

5 Pathways to Electrification of Mobility

There are several clear pathways to electrifying mobility in Africa or India. However, the Indian government is already facilitating the purchase of new EVs so these pathways focus on Africa. Each of these pathways could be designed, either with an integrated battery, or to interface with a battery swap system (where the battery is charged external to the vehicle and swapped when the battery in use is discharged); see the Appendices for further details. Battery swapping has the advantage of minimising impact on the power network. This is because batteries are dissociated from vehicles driving patterns and thus can be charged at any time of day, making EV battery charging even more flexible. The main disadvantage is cost. More batteries are needed in the system in order to be sure that a fully charged battery is available when a vehicles arrives at a battery swap station. Below are the four main pathways to electrification.

- Import new vehicles already manufactured for High Income Countries (e.g. private cars or buses):

- **Pros** Vehicles already available, see Table 3; simple purchase; battery swap buses already exist in China.[63]
- **Cons** May not meet all the modality needs of African transport; price point may be too high because marketed at higher income countries; additional carbon is embedded from manufacturing the vehicle body.

- Import new vehicles specifically designed for low- to middle-income countries (e.g. auto-rickshaws and electric motorcycles):
  - **Pros** Vehicles designed to meet the needs of African transport; designed to be sold at a cheaper price point; e.g. battery swap auto-rickshaws being trialled in India.[64,65]
  - **Cons** Delay probable while the vehicles are designed and scaled up to the mass market; price may still be too high, especially because demand may be lower than for vehicles manufactured for High Income Countries; additional carbon is embedded from manufacturing the vehicle body.

- Manufacture new vehicles appropriate for African transport needs in Africa:
  - **Pros** Vehicles designed to meet the needs of African transport; local job creation; proof-of-concept vehicles already been manufactured (e.g. the Kantanka Odeneho II in Ghana, the Kiira EV in Uganda, the Joule in South Africa, and the Lion Ozumba 551 in Nigeria[66]).
  - **Cons** Vehicles may still be relatively expensive; requires technical expertise and large scale manufacturing equipment – time and money is needed and will likely require Original Equipment Manufacturers (OEMs) to expand into African market; additional carbon is embedded from manufacturing the vehicle body.

- Retrofit existing vehicles with an electric drive-train in Africa (removal of the internal combustion drive-train and replacement with an electric drive-train; vehicle body remains the same):
  - **Pros** Cheaper than purchasing new vehicles; likely to be a grass-roots creation of local industry, develop local skills, create local jobs, and create a workforce for OEMs to utilise if needed; reduced waste as body of the current vehicles is kept (i.e. some of the embedded carbon from manufacturing new vehicles is avoided); re-use of the vehicle body avoids need for specialist skills associated with developing cost-effective body-manufacturing processes; already well-practised,[67] with EV conversion kits now widely available[68] and start-ups emerging in this space;[69] could offer a stepping-stone to manufacturing the full vehicle in Africa.
  - **Cons** Requires technical expertise for the retrofit – time and money needed (but less than for complete vehicle manufacture); policy hurdle regarding retrofitting homogeneity regulations; because the national benefits are significant and would be felt by local economy, this could be expedited and should be supported by policy.

Considering the four pathways to electrifying mobility, there may be a small market for new EVs designed for high income countries, for those who can afford them or who wish to set an example (e.g. senior members of government). This may be useful in driving aspiration and acceptance of EVs. However, for most of the population, mobility tends to be utilisation and not a status symbol. Therefore, the majority are likely to reach the market via the three other pathways because of the reduced access to capital. For certain modalities it could be more appropriate to import new vehicles designed for the low- to middle-income use-cases. Motorcycles, for example, are difficult to retrofit with electric drive-trains because of their design – the compact packaging and delicate weight balance does not lend itself to retrofit. Therefore, it is better to design these from scratch as EVs, as has been done by several companies already, see Table 3. The same could be said for auto-rickshaws. Manufacturing vehicles in Africa is a great opportunity to create local industry and jobs. However, the capital necessary to establish assembly lines for multiple vehicle models may be challenging to acquire, except in South Africa, where there is a well established auto manufacturing and assembly industry. On top of this, the time to build this manufacturing capacity and train the workforce may result in excessive lag times before locally manufactured vehicles are available at scale. It is unclear what the cost savings compared to importing EVs would be. Retrofitting vehicles allows a lower cost mechanism to electrify mobility while creating local jobs. It also avoids the carbon embedded in the bodies of new vehicles. In fact, retrofitting could be a stepping stone to developing local vehicle manufacturing, requiring less capital, less training, and less manufacturing equipment.

One knowledge gap to highlight is the lack of government-level, country-specific analysis of appropriate pathways and identification of the necessary policy to support each of these. Such tasks are completed in the UK by the Committee on Climate Change (CCC) and Office for Low Emission Vehicles (OLEV).

5.1 Financial Implications for the End User

An important financial calculation when investing in electrifying a vehicle is the payback time needed for the end user to recover their investment. Consumer uptake of the technology will play a major role in its success and therefore affordability is important. Due to the lack of end user capital, two business models are likely. The first is when the vehicle is owned by a third party and leased by the end user. In this case, payback time is important for the third party as it heavily impacts business finances. The second will be a loan to the end user, paid off over the vehicle payback time. The shorter the payback time, the lower the cost of finance will be and the sooner the debt will be repaid. Therefore, it is useful to identify driving patterns that shorten the payback time and increase end user uptake.

The payback time can be calculated by considering the cost of investing in retrofit (i.e. an uplifted battery cost to include labour and financing), and the cost savings per kilometre driven (i.e. the difference in fuel cost per kilometre). There will be a certain distance that the vehicle has to travel before the investment is repaid. Therefore, the time this takes depends on the driving pattern of the vehicle. This is the case for both new and retrofitted vehicles, but for retrofitted vehicles the cost is likely to be lower, and therefore recovered faster.

This will only be valid when electrification offers an advantage by reducing running costs, which depends on the cost of petrol and electricity in each country as well as how much more efficient the electric version of the vehicle is. Figure 6 compares the cost of fuel in African countries. Lines have been added for each modality that relate to the ratio of EV fuel efficiency compared with internal combustion engine efficiency. This means that for the countries that have petrol prices above the line, electricity will be a cheaper fuel than petrol, see the Appendices for details on calculations. Figure 6 also indicates the carbon intensity of the electricity grid compared to using oil, shown by the colour of the circle. If it is below 1, one can consider that it is environmentally beneficial to switch to an EV.

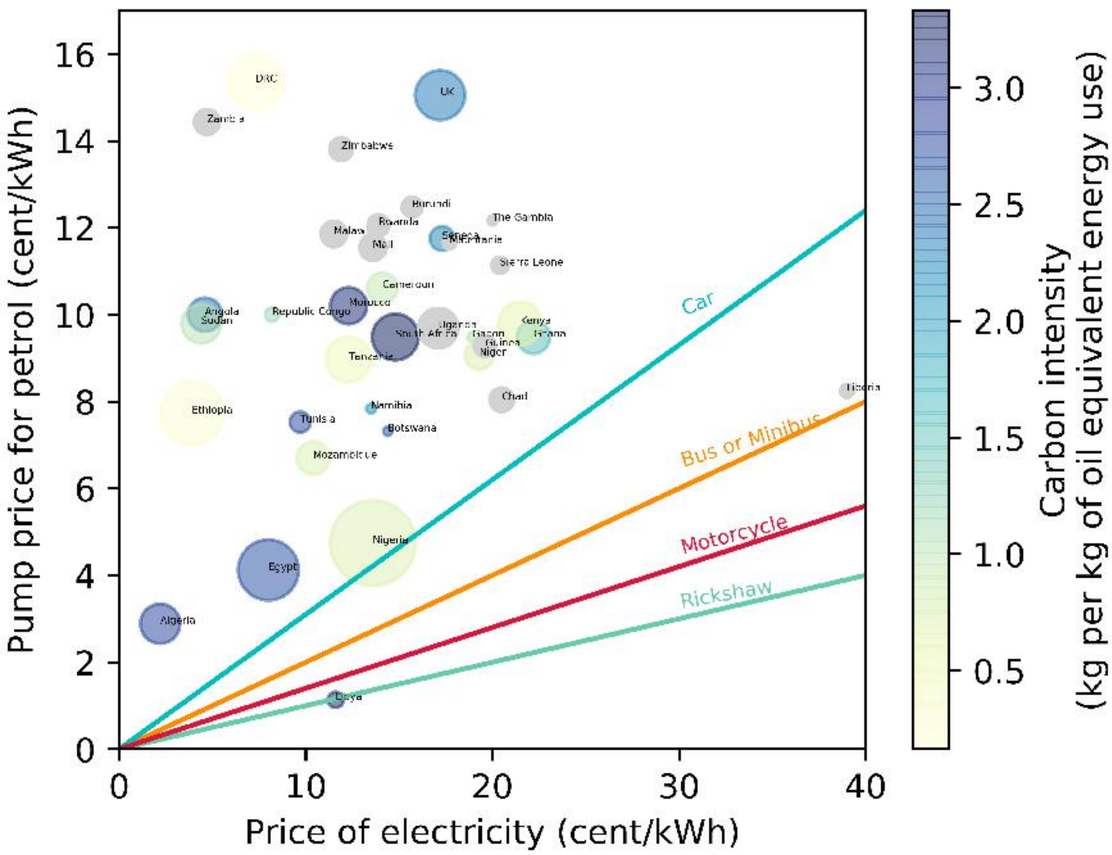

Figure 6: Price of petrol[51] against price of electricity[70] for the majority of African countries and the UK. The size of the marker is proportional to population.[5] The carbon intensity[71] of the electricity grid is indicated by the marker colour. Where carbon intensity data were unavailable, markers are displayed as grey. Lines represent the difference between EV and internal combustion engine fuel efficiency, details in the Appendices. Markers above the line indicate countries where the running costs of an EV would be cheaper than that of an internal combustion engine.

It is clear that for the majority of modalities, in the majority of countries, fuel costs will be cheaper when running an EV than an internal combustion engine.

Using this data, Table 4 offers a guide to payback times for transport modalities under the following assumptions. The battery cost was taken as 150\$/kWh,[72] and uplifted to 220\$/kWh to include cost of labour and financing.[73,74] The pump price of petrol is calculated as 10 cent/kWh equivalent and the price of electricity is 12 cent/kWh (taken from Figure 6). The higher efficiency of the EV is taken into account as in Figure 6.

Mode	Driving Range Between Charges (km)	Payback Time (years)
Buses	60	3
Minibuses	250	3
Private cars	200	5.5
Auto-rickshaws	150	2
Motorcycles	250	1.5

Table 4: Payback time on investment to retrofit a vehicle with an electric drive-train

The payback time for some of the modalities is relatively short, in the order of 1-3 years, which is reasonable to attract investment. Private cars, however, are seen to need a longer payback time. As discussed previously, despite the attractive payback time for motorcycles, because of their design it could be preferable to purchase EVs rather than retrofit.

Note that, for a bus to have a manageable battery size (below 100kWh), the bus range is limited to 60 km in Table 4. This would only be suitable for a minority of journeys according to Table 1. This is not the case for minibuses. However, the system has been proven to work in China using buses with a battery swap system, so the challenge of battery capacity is not insurmountable.[27]

The calculated payback times make motorcycles, auto-rickshaws, minibuses, and buses the obvious candidates for initial electrification. Depending on which pathway is taken, the timing of this transition is likely to be within the next decade for these vehicles, which offer a high-value proposition. In other words, these modalities have low capital costs and high utilisation, which results in a short payback time, after which they begin to generate profit. To prepare for this, countries should be investing in scale-up of renewable energy generation to provide sufficient low-cost energy. This should be co-located with charging hubs to avoid widespread need to upgrade the distribution network. This leads us to the remaining question: what is the impact of all this on the power system?

6 The Impact of Electric Vehicle Charging on the Power System

Charging EVs requires power, so electrifying transport will have an impact on the operation of the electrical grid.

However, the impact of EV charging depends on the type of EV charger, its location in the system, and the flexibility of when the vehicle can charge (as will be discussed later). Table 5 summarises the charger speeds currently available in the UK. Different chargers are suitable for different business models: buses and minibuses that run regular services have large batteries and will need to be charged quickly between trips, therefore rapid charging is most appropriate; motorcycles have much smaller batteries so can be charged in a relatively short amount of time using a slow or fast charger; private vehicles have medium-sized batteries but are often unused for hours at a time, so slow charging is likely to be sufficient. Slow chargers can be connected to residential networks so are often private, whereas rapid chargers need to be connected to the higher voltage system and are typically public.

Connector	Speed	Power (kW)	Mode	Charging Time*
Type 1/Type 2	Slow	3.5	AC	8 hrs
Type 1/Type 2	Fast	7	AC	4 hrs
Type 2	Fast	22	AC	80 mins
Type 2	Rapid	43	AC	35 mins
CHAdeMO	Rapid	50	DC	30 mins
CCS	Rapid	50	DC	30 mins
Type 2	Rapid	120	DC	12.5 mins

Table 5: A description of the types of charger currently available in the UK. *Approximate time taken to charge a 30 kWh battery from 0% to 80%.

In terms of the impact on power system operation, there are implications for both the national scale system and the local networks to which vehicles are connected.

6.1 National System

At the national level, there must be a balance between the total power flowing into and out of the grid at any time. This means that power generation needs to be matched to power demand in real time. An increase in the national peak demand will therefore require an increase in the installed power generation capacity.

As an example, Figure 7 gives an indication of what the power demand profile might be in Kenya with electrified motorcycles, minibuses, and private vehicles, without smart charging. Private vehicles are assumed to charge predominantly in the evening, minibuses are charged at regular intervals, and motorcycles are charged more uniformly throughout the day.

Buses and auto-rickshaws are not included. Buses are not included because of the limited driving range calculated and shown in Table 4 and because of a lack of data about driving patterns. Rickshaws are not included because they tend not to be a dominant modality in Africa according to Table 2.

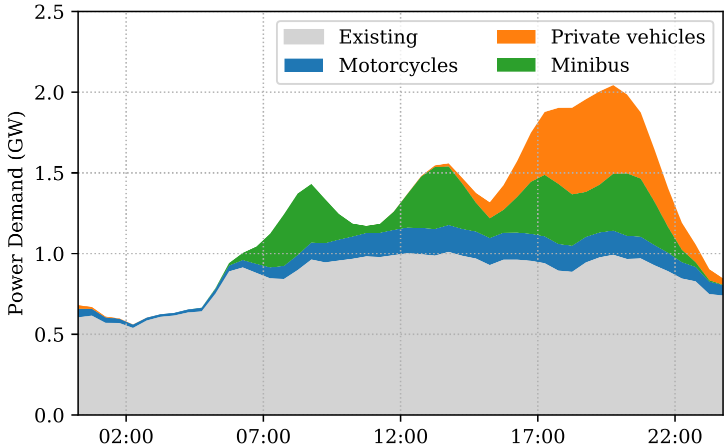

Figure 7: The Kenyan national power demand profile with the addition of electrified transport by the authors. Without smart charging.

The modalities are ordered in Figure 7 as motorcycles, minibuses, and then private vehicles because the previous sections of this report have provided insight that would suggest motorcycles and minibuses should be electrified first, followed perhaps by private cars. The reason for this is that motorcycles and minibuses often operate intra-town, requiring less investment in network infrastructure; they appear to have reasonable payback times; and the demand is likely to increase due to urbanisation. All vehicles of these modalities are assumed to be electric in this instance. The values are indicative and more data are required to verify these initial calculations.

Figure 7 shows that, compared to the current power demand in Kenya, the additional EV charging demand doubles the peak power demand, meaning that twice as much power generation would be required in order to meet demand. Achieving this would be capital intensive. However, this drastically increased requirement for generation capacity can be avoided by changing the time at which vehicles are charged. This is often referred to as smart charging.

6.2 Smart Charging

EV charging can be considered an elastic demand because it does not matter to the vehicle owner when precisely the charger is drawing power, provided the battery is charged by the time the vehicle is needed. This means that the impact of EV charging on the power system can be reduced by coordinated charging – smart charging.

Smart charging can involve either shifting the demand in time or reducing the power demand of individual chargers. The flexibility of individual vehicles will depend on their availability; privately owned vehicles are likely to be the most flexible, while service vehicles often operate on a tight schedule. Minibuses are assumed to do two runs a day, morning and evening. They therefore offer some flexibility as there are moderate lengths of time throughout the day when they are not in use. These assumptions would benefit from real-world data, an this is highlighted as one of the knowledge gaps. However, smart charging could also take the form of battery swapping (where the spare batteries are charged at off-peak times) which would offer enhanced flexibility for service vehicles by decoupling charging from vehicle use.

Nationally, smart charging can reduce the peak power demand, meaning that demand could be met with a smaller amount of installed power generation. This is shown in Figure 8 for the same Kenyan example as in Figure 7. It is assumed that motorcycles are not flexible, minibuses are relatively flexible, and private vehicles are fully flexible. For this scenario, if charging was optimally controlled, the peak demand would be reduced to 1.25 GW – only a 25% increase on the existing demand, instead of 100% as seen in Figure 7.

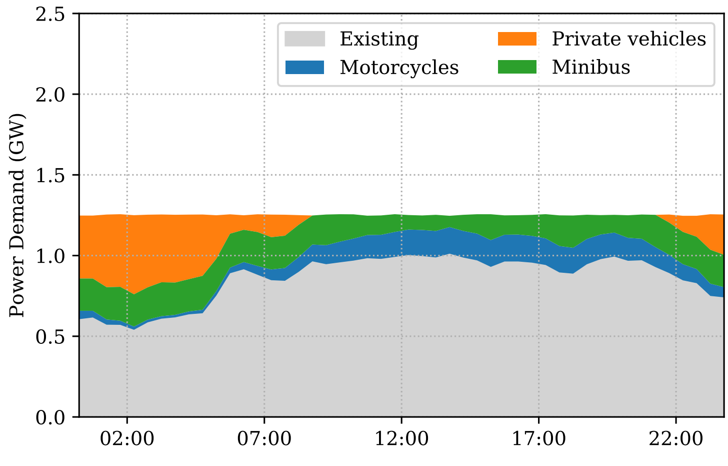

Figure 8: The Kenyan national power demand profile with the addition of electrified transport by the authors. With smart charging. Assuming user behaviour: motorcycle charging is inflexible, minibuses are relatively flexible, and that private vehicles are fully flexible regarding when they charge.

Vehicles could either be coordinated in a centralised manner,[75] where one central actor directly controls the charging of a group of vehicles, or in a decentralised manner,[76] where each vehicle controls its own charging in response to a price signal. Either way, additional communication infrastructure is required to implement smart charging. Some papers propose using a tariff scheme to control charging[77] such that there are predefined cheaper hours of electricity, but this has been shown to cause artificial peaks in demand.[78]

6.3 Local System

Depending on the position and power rating of the EV chargers, EV charging may also cause problems in the local network.

For private vehicles, 3.5-7 kW chargers that are privately owned may be the obvious choice. These chargers are often positioned in residential low-voltage networks. In this location, they can represent a comparatively large and sustained load; this may overheat the transformer connecting the network or result in unacceptably low voltages further down the network.

Alternatively, for service vehicles, a central charging hub may be more suitable, both for mobility logistics and charger infrastructure. In this case chargers are higher power (50 kW or greater) but positioned in the higher voltage network. These chargers are on for much shorter periods of time, but it is likely that all available chargers could be used simultaneously. In this case local voltage or transformer problems are less likely, but there may be issues with the loading of local lines or the frequency stability.

Smart charging could offer the local advantage of enabling the power available to an individual charger to be controlled. This could then be reduced if the network was constrained – e.g. if the voltage is too low or if the transformer is near its operating limit.

7 Knowledge Gaps and Priority Research Questions

One of the aims of this report is to highlight the knowledge gaps and priority research associated with decarbonising transport in Africa and South Asia. Five knowledge gaps are identified and recommendations on how to address these are summarised below.

- Data on the number of vehicles used for each modality in every country: as is evident from Table 2, the number and type of vehicles on the road is unclear. These data are necessary to understand the impact on the electricity system and thus the most suitable pathways to electrification. Initially, this will require close work with the relevant in-Country Department to gather and release the official list of registered vehicles. This could be achieved through policy surrounding vehicle registration. In some cases, the data may already exist but may need to be made accessible, for example through implementation of open-access policy surrounding the records. It is noted that in some countries there may be a number of informal, unregistered vehicles; this may require a more politically sensitive approach to determine the number of these vehicles.

- Data on modality use in each country: there is a lack of data surrounding how vehicles are used and how this differs seasonally and geographically.

  There are different levels of detail at which this data could be collected in order to identify how modalities are used. The minimum useful data would be national numbers of vehicle types and the annual mileage of each vehicle, but assumptions would have to be made about vehicle use pattern.

  A more useful dataset, in addition to the above, would be a transport survey. For example, the UK National Travel Survey[79] gives a broad overview of all trips. It records vehicle modality, time of trip, distance, purpose of trip, and location of departure for over 14,000 individuals for a week using a travel diary. This approach may be culturally challenging in some regions of Africa.

  A more detailed dataset could be acquired by GPS tracking a sample of vehicles. The advantage is that it will provide the accurate route of the vehicles, but it will not give details of the number of passengers. For example, the company CleanCar[80] offers this service in the UK and is currently tracking hundreds of internal combustion engine delivery vans to assess their suitability for electrification as part of the Innovate UK funded Vehicle-to-Grid Oxford (V2GO) project.[81] The granularity of this data allows calculations of energy consumption per trip, which would be useful in determining the impact on the power network. This, coupled with a travel survey, would provide useful insight into the transport modality use and therefore power network impact. Although V2G could offer additional services and mechanisms to support increased renewable generation (discussed in the Appendices), there is a knowledge gap around what regulation and price structures are necessary to facilitate uptake of V2G.

All of these need to be supported by the necessary policy frameworks, which may differ from those in high-income countries and thus require further consideration.

- Understanding the challenges associated with the pathways to electrify mobility, especially considering retrofit from internal combustion engine to battery electric: demonstration projects are needed to understand "real" costs and on-the-ground logistics. The focus could be on minibuses for mobility services, which promise to offer high impact for mobility decarbonisation due to their high passenger miles. Minibuses are an obvious target vehicle, not only because they are suitable for retrofit, but also because they show payback time on investment of under 3 years for the end user; they are likely to become more popular with urbanisation; they operate in urban areas; and they are often based at transport hubs, meaning network reinforcement would be concentrated. Data from knowledge gaps 1 and 2 will be needed for these economic and business analyses. Policy to enable the growth of a formal retrofit industry will be necessary in order to allow licensing of non-homogeneous vehicles while the industry develops.

- Determining the specific impact on each country's power network from generation required to impact on the distribution system: the optimal location for vehicle charging infrastructure and the rating of the charge points will depend on the modalities electrified and their driving patterns (again indicating the vital importance of knowledge gaps 1 and 2). For the distribution network, the introduction of charging points could result in congestion due to concentrated demand (i.e. at hubs). This may require network reinforcement in the form of more wires or it could be relieved by co-located generation such as solar PV. At the transmission network level there must be sufficient generation to account for increased demand. This may require further low-cost, low-carbon generation to be added to the system. If generation is co-located with the demand, this will reduce strain on the distribution network. To identity the appropriate policy surrounding location and capacity of additional clean energy generation and distribution network upgrades, knowledge gaps 1 and 2 need to be addressed. Policy mandating smart charging technology should be considered to avoid drastic affects on the power network.

- Smart charging vs battery swap and knowing economically and logistically which would be preferable (taking into account the power network): when electric mobility is brought to scale, dumb charging could cause a substantial increase to the maximum power demand. For example, for the UK, uncontrolled charging of a fully electrified UK fleet could lead to a 50% increase in the peak power demand, whereas smart charging could mitigate this increase completely.[82] In Kenya, indicative results for smart charging were able to limit the increase in peak demand to 25% (Figure 7) instead of 100% (Figure 8) for uncontrolled charging. Therefore, it is likely that an advanced charging strategy will be needed to minimise impact. This could be through battery swap schemes or smart charging. However, the business models and technical requirements vary between the two. To analyse which is superior, knowledge gaps 1 and 2 must be filled. On top of this, demonstrations would be advisable to improve understanding of the real world technical, economic, and business challenges. Battery swap models have been effective for buses in China[63] and motorbikes in India,[65] but the African context is different, which is why in situ trials are important.

From a policy perspective, in order to identify the appropriate pathways to electrification and to develop policy which would support this transition, the above knowledge gaps will need to be filled. However, on top of this, several policy challenges will need addressing regardless of pathway. Firstly, registration of EVs must be facilitated. Secondly, battery supply and end-of-life should be regulated to maintain ethical and environmental standards. Thirdly, mechanisms to recover any fuel taxation loss must be considered.

Depending on which pathway is taken, the timing of this transition could be within the next decade for vehicles with a high-value proposition, such as retrofit of minibuses. High-value proposition modalities have a low capital cost for electrification and high utilisation, which results in a short payback time, after which they begin to generate profit. To prepare for this, countries should put policy in place to be investing in scale-up of renewable energy generation to provide sufficient low-cost energy, co-located with charging hubs to avoid widespread need for distribution network upgrade. Financing of this could come from reduced subsidies for fossil fuels.

8 Conclusions

This report suggests that EVs would be the most appropriate low-carbon road-transport alternative for Africa and South Asia. EVs are already at mass manufacture, require reduced energy consumption compared to internal combustion engine vehicles, are able to offer substantial reductions in CO_2 emissions if the electricity is generated from a low-carbon fuel mix, and the power distribution infrastructure is already developing (if not fully developed).

The nature of passenger transport in Africa and South Asia is heavily service vehicle-based, with only 2% of individuals in Sub-Saharan Africa owning private cars.[13] Therefore, it is concluded that the most suitable vehicles to electrify first are the minibuses, motorcycles, and auto-rickshaws (location dependant) because: they cover the furthest distance per day and are the modality of choice for the majority of people; they are intra-town-based vehicles, so the demand for these modalities is likely to increase as urbanisation continues; and their operation intra-town means that network reinforcement (either grid or increased generation) is restricted geographically to one area, thereby reducing the cost.

On top of this, the potential to retrofit electric drive-trains into the existing minibuses is promising. Retrofitting provides local industry and job creation, reuses the body of the vehicle (thus reducing embedded carbon), is a cheaper alternative to purchasing EVs new, and the payback on investment is generally in the order of 3 years.

Opportunities for electrifying vehicles are identified as a means to reduce dependence on imported fuel, an abundance of solar energy available to be harnessed as low-cost electricity, improvements to air-quality, increased utility company revenue, potential job creation, a technology-open society, and, in some cases, engaged governments.

The impact on the power sector of introducing EVs is found to depend heavily the use of smart charging (i.e. adjusting the time of day at which the vehicle is charged to reduce impact on the power network). This indicates that smart charging or battery swap models will likely play an important role.

The key knowledge gaps are identified to lie at the interaction between the mobility system and the power system: firstly, the number of vehicles and vehicle type in each country; secondly, the driving patterns of the different modalities; thirdly, a detailed cost-benefit analysis of the different pathways to introduce electric mobility (retrofit or purchase); fourthly, an in-depth analysis of the impact on the power network; and finally, country-specific business cases for mechanisms to reduce the impact on the power network (battery swap or smart charging). Filling these knowledge gaps will help greatly in informing the development of country-specific policy and regulation to assist with EV uptake.

9 Appendix I: Alternative Fuel Vehicles

9.1 Biofuel Vehicles

One potential route to reducing carbon emissions is to modify internal combustion engines to run off greener fuels, specifically natural gas or biogas. These could be dispatched in the same way as petrol, in service stations supplied by delivery trucks.

Natural gas is a non-renewable hydrocarbon, but it produces 25-30% less CO_2 per joule delivered than oil.[83] Compressed natural gas can be used to fuel vehicles, thereby reducing tail-pipe emissions of the vehicle. Biogas is a renewable energy source as it can be produced from raw materials such as food waste that have absorbed carbon dioxide during their growth. It can either be produced by anaerobic digestion of materials or by using thermal gasification (where materials are reacted with oxygen at high temperatures).

When considering the value of alternative fuels, it is important to include the energy required for processing and distribution of the fuel in the comparison. This is commonly referred to as a well-to-wheel analysis. Figure 9 shows the reduction in emissions and total energy consumption of biofuel vehicles to petrol vehicles.[84] All three fuel types resulted in an increase in total energy expenditure compared to petrol vehicles, largely due to the energy required to compress the gas. The additional energy will increase the total emissions, but all fuels still resulted in a well-to-wheel emissions reduction compared to petrol vehicles. Compressed natural gas achieved only a small reduction, whereas biogas vehicles mitigate the majority of the carbon emissions. Achieving this reduction requires minimisation of methane losses (e.g. methane boil-off in storage tanks) and efficient operation of low-carbon delivery trucks.

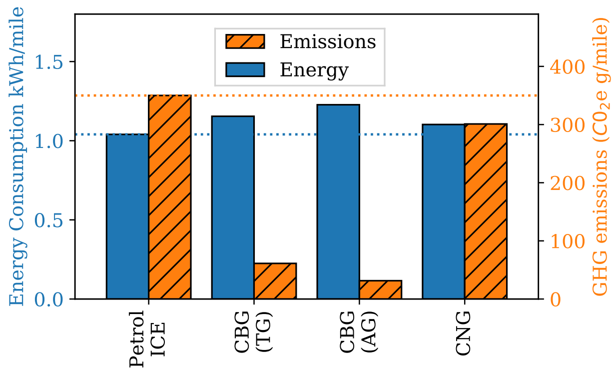

Figure 9: The emissions and energy consumption for various biofuel vehicles, compared to petrol vehicles. CNG: compressed natural gas, CBG: compressed biogas, TG: thermal gasification, AD: anaerobic digestion.[84]

9.2 Hydrogen Vehicles

Hydrogen has been suggested as an alternative fuel. It is possible to modify internal combustion engines to run off hydrogen, but cleaner and more efficient vehicles can be produced by using hydrogen fuel cells in combination with an electric motor. The improvement in efficiency and the reduction in greenhouse gas emissions compared to conventional vehicles depend on the methods used to produce and distribute hydrogen. Hydrogen can be transported as either a compressed gas or in liquid form. Liquefying hydrogen is an energy-intensive process, but it can then be transported more efficiently. The distance that the hydrogen must be transported dictates which option is more efficient.

The cheapest and most efficient way to produce hydrogen is steam reformation, where natural gas is reacted with high temperature steam. This process is not energy-intensive, but carbon dioxide is produced as a by-product. The overall energy and carbon efficiency of this process depends on where the hydrogen is produced – which could either be done centrally, or at local stations to which natural gas is distributed using pipelines. Alternatively, hydrogen can be produced by using electrolysis to split water. This process does not directly produce CO_2, but does use a significant amount of electricity – meaning the carbon intensity depends on the fuel mix used to generate electricity.

Figure 10 displays the results of an analysis[85] which compares the emissions and energy consumption of hydrogen vehicles using various production techniques with petrol internal combustion engines. Natural gas can reduce well-to-wheel emissions by more than 50% compared with petrol vehicles when hydrogen is produced centrally and transported as a compressed gas. The emissions reduction achieved with electrolysis is highly dependent on the source of electricity – using the US fuel mix increases the total emissions, while a 100% renewable fuel mix would reduce them to zero.

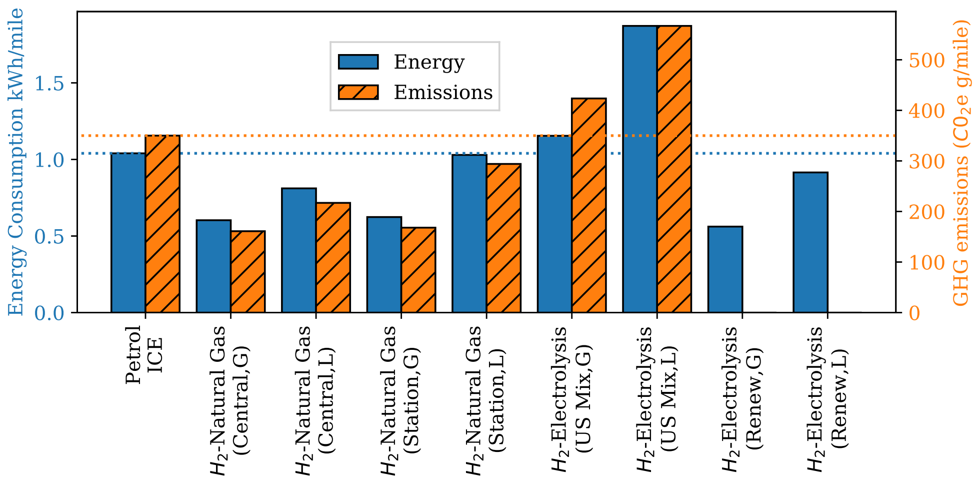

Figure 10: The emissions and energy consumption achieved with hydrogen vehicles using various production and distribution technologies, compared with petrol vehicles[85]

9.3 Available Alternative Fuel Vehicles

Table 6 summarises the technical or market status of the alternative fuel vehicles. If models are available, examples are specified. Please note that, for biofuel, B100 is 100% bio-diesel and ED95 is 95% bio-ethanol.

	Biofuel (B100, ED95)	Hydrogen[86]
Buses	**Purchase possible**: Europe[87] **On trial**: South America[88]	**On trial**: Europe[89] (*JIVE project*[90,91]), USA,[92] China,[93,94] Japan,[95] India[96]
Minibuses	**Minimal attention** Note: In many countries fossil petrol and diesel already contain a small proportion of biofuels (less than 5 %). Engine retrofit necessary to run off pure biofuels.[97] However, these engines exist (see cars).	**Prototype**: Hyundai minibus[98] Toyota minivan[99]
Cars	**Purchase possible**: Flex-fuel vehicles popular in Brazil which can run on either petrol or biofuel[100]	**Purchase possible**: USA,[101] Japan,[95] Europe[102] **R&D investment**: China[25]
Rickshaws	**Minimal attention** Note: as for minibus	**On trial**: India (2012)[103–105] Germany (2012)[106]
Motorcycles	**Minimal attention** Note: as for minibus	**Purchase possible**: Pragma (bicycle)[107] **On trial**: UK[108] **Under development**: Honda[109]

Table 6: Alternative fuel low-carbon vehicle status in 2019 by transport modality and fuel type

10 Appendix II: Technology Horizon

Low-carbon transport currently receives much research and development funding. On top of incremental improvements to market-ready technologies, the focus areas of note are ammonia, new battery technologies, V2G, and battery swap models. The majority of these technologies would open up alternative business models.

10.1 Ammonia

Ammonia is one of the most widely used chemicals globally. Historically, it has predominantly been used in the fertiliser industry. However, in recent years it has shown great promise as a hydrogen carrier. Ammonia (chemical formula: NH_3) can be used in a direct ammonia fuel cell (DAFC), or "cracked" by heating to give nitrogen (N) and hydrogen (H), which can be used in hydrogen fuel cells.

The majority of ammonia is presently produced by steam methane reforming (SMR), which releases CO_2. This is termed "brown" ammonia and cannot be considered low carbon unless carbon capture and storage is employed, in which case the ammonia is colloquially referred to as "blue" ammonia. In order to produce "green" ammonia, green hydrogen is required. This can be manufactured from the electrolysis of water, splitting the H_2O into hydrogen and oxygen. However, this requires a low-carbon electricity mix as it is an energy-intensive process. The green hydrogen can then be combined with nitrogen through a number of alternative mechanisms.

Pros: Ammonia is a more stable hydrogen carrier than hydrogen itself and is more power dense.[110] There is already widespread ammonia production and storage infrastructure, which can be expanded while R&D continues.

Cons: Requires an extra step compared to hydrogen fuel cells because ammonia must first be made from hydrogen, thereby reducing the round trip efficiency.

Infrastructure Requirements: Ammonia would require its own storage and transportation network; separate to the power infrastructure. However, the process of manufacturing ammonia will require power, so the two will not be completely decoupled. Depending on the production route used to manufacture ammonia, the power requirements will vary. One important differentiation between EVs and chemically powered vehicles is that the generation of the chemical can be decoupled in time from the demand to re-fuel a vehicle. This opens up the opportunity to generate the chemical (either hydrogen, or ammonia) at a time that is most suitable to the power sector.

10.2 New Battery Technologies

New battery technologies are being developed to decrease the cost, often referred to as post Li-ion. Either by increasing the energy and power density of batteries, ideally resulting in lighter and cheaper batteries due to a reduction in material use, or using cheaper materials. For example, Na-ion batteries are attracting attention as lower cost means of achieving comparable power density to Li-ion.[111]

Pros: Reduced material use could reduce pressure on resources. Diluting societal dependence on a small number of materials, by expanding battery technologies available (i.e. to Na-ion), may ease potential political tensions. Any reduction in price of batteries that allows wider access to EVs will hasten decarbonisation of transport.

Cons: Still at the early stages of R&D with transport decarbonisation action needed imminently. The search for an alternative, affordable technology that relies on abundant, non-toxic elements may be unsuccessful.

Infrastructure Requirements: For post Li-ion batteries, if battery capacity is increased instead of remaining constant, it could result in a need for higher-power charge points.

10.3 Vehicle-to-Grid (V2G)

V2G is the use of an EV battery as an energy storage asset on top of the primary use of the battery to provide mobility. It differs from smart charging (alternatively termed V1G), where power to the vehicle is controlled and optimised, because power can flow both to and from the vehicle battery. In its two simplest forms, V2G can offer power network support to the operator or a behind-the-meter battery to the vehicle owner. Both of these are made appealing by a financial incentive to the vehicle/battery owner. V2G is in the early stage of technical implementation, with the major challenges being the business case. Innovate UK have invested £40 million in projects running 2018-2021 in an attempt to accelerate progress.

Pros: V2G is able to provide frequency and voltage response to the power network (which is necessary with intermittent renewable energy generation) as well as demand turn-up or turn-down to accommodate renewable energy generation on the network. There is limited upfront capital cost because the vehicles and infrastructure have already been purchased for their primary mobility function, so the only additional cost is for the bi-directional functionality, the optimisation and control platform, and any battery degradation. By employing V2G, it may be possible to mitigate the need for costly improvements to the distribution network capacity.

Cons: Vehicles must be parked and plugged into a bidirectional charge point in order to perform V2G. V2G may result in battery degradation. For power network use, a sophisticated optimisation and control program is necessary, which may incur an additional cost.

Infrastructure Requirements: V2G works to support the power network by effectively offering flexible load and generation as well as ancillary services. However, V2G does require bidirectional charging infrastructure that is capable of meeting the power ratings of the EV batteries connected to them.

10.4 Battery Swap Models

EV battery swap is an alternative to the conventional model (where each EV contains a battery that remains inside the vehicle and is charged by the driver repeatedly). In the battery swap model, once the EV battery is nearly drained from driving, an EV driver will take their vehicles to a battery swap depot for battery exchange. The present battery is removed and exchanged for an alternative (fully charged) battery so the driver can drive off immediately. The initial battery is charged at the depot at low power, and the cycle repeats.

Pros: EV battery charging becomes a more flexible load and can be done at lower power because the customer is not waiting. Low power charging puts less strain on the power network due to reduced power demand. Charging could also be smart to make the most of renewable energy generation or smooth demand. Low power charging is also better for the battery and therefore may result in longer battery lifetimes. EV drivers do not have to wait for their batteries to be charged.

Cons: A greater number of EV batteries are needed in the system. The business model has been seen to provide financial challenges, such as Better Place.[112] EVs need to be designed especially to enable rapid battery exchange. Battery ownership is not straightforward. Advanced redistribution algorithms are needed to make sure batteries are available in the necessary locations.

Infrastructure Requirements: The demands on power infrastructure could be reduced if the number of batteries is sufficient to allow low-power, flexible charging. Channels to redistribute the batteries will be necessary, which will depend on local transport infrastructure.

11 Appendix III: Figure 6 Data

The lines shown in Figure 6 were calculated from miles per gallon data, which was converted into miles per kWh energy stored in the fuel. This was compared to mile per kWh data for the equivalent EVs. The data used, and references, are shown in Table 7. The conversion from gallon of fuel to equivalent kWh was 9.6 kWh/litre[113] (43 kWh/gallon).

Modality	ICE (mpg)	ICE (miles/kWh)	EV (miles/kWh)
Buses	5.3[114]	0.1	0.5[115]
Minibuses	27[116]	0.6	3.1[117]
Cars	51[118]	1.2	3.8[119]
Rickshaws	53[120, 121]	1.2	12[122]
Motorcycles	57[123]	1.3	9.3[124]

Table 7: Indicative values for fuel consumption by modality and fuel type (ICE: Internal Combustion Engine and EV: Electric Vehicle)

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