Electrification of minibus taxis in the shadow of load shedding and energy scarcity

AUTHORS:
Marthinus J. Booysen[1,2]
Chris J. Abraham[1]
Arnold J. Rix[1]
Johannes H. Giliomee[1]

AFFILIATIONS:
[1]Department of Electrical and Electronic Engineering, Stellenbosch University, Stellenbosch, South Africa
[2]Department of Industrial Engineering, Stellenbosch University, Stellenbosch, South Africa

CORRESPONDENCE TO:
M.J. Booysen

EMAIL:
mjbooysen@sun.ac.za

HOW TO CITE:
Booysen MJ, Abraham CJ, Rix AJ, Giliomee JH. Electrification of minibus taxis in the shadow of load shedding and energy scarcity. S Afr J Sci. 2022;118(7/8), Art. #13389. https://doi.org/10.17159/sajs.2022/13389

ARTICLE INCLUDES:
☐ Peer review
☐ Supplementary material

KEYWORDS:
minibus taxi, paratransit, electric vehicle, decarbonisation, load shedding

PUBLISHED:
15 June 2022

1 NO POVERTY
7 AFFORDABLE AND CLEAN ENERGY
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
10 REDUCED INEQUALITIES
11 SUSTAINABLE CITIES AND COMMUNITIES
12 RESPONSIBLE CONSUMPTION AND PRODUCTION
13 CLIMATE ACTION

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Significance:

Electrification is expected to decarbonise transportation and forms part of the agenda to delay climate change. Electric vehicle sales have ballooned and production of combustion engines will stop soon. In sub-Saharan Africa the transition is slow. Minibus taxis carry more than 70% of commuters and little is known about their electrification requirements. Electrical demand planning is better with vehicle-based data than with passenger-based data. Stationary times provide ample time for taxis to recharge from the grid and solar, but the latter requires substantial stationary battery capacity to negate grid-impacting fast charging. Taxi energy requirements are approximately 200 kWh/day on average.

Electric vehicles are heralded as a silver bullet to globally decarbonise the fuel-guzzling transport sector. The Intergovernmental Panel on Climate Change (IPCC) estimated in 2014 that the transport sector generated 23% of the global energy-related greenhouse emissions.[1] The development of low-carbon transport in cities is part of the global agenda to delay climate change[2] and relates to three of the United Nation's Sustainable Development Goals[3]. Meanwhile, electric vehicle sales have increased substantially in the Global North and many global vehicle manufacturers plan to stop production of combustion engines as early as 2030.

However, in sub-Saharan Africa, the transition to electric vehicles continues to be painstakingly slow. Privately owned minibus taxis (MBT), the mainstay of transport in the region, are ubiquitous in the developing cities and rural areas of sub-Saharan Africa. They cater for 83% of the so-called 'paratransit' industry, which carries more than 70% of daily commuters in sub-Saharan Africa. This informal sector is now faced with the need to transform to an electrical energy source.[4-8] Currently, very little is known about the energy requirements of MBT, especially given their unique and mostly unknown mobility patterns.[9]

This uncertainty on the vehicle side of this revolution is further overshadowed by the looming threat of energy scarcity on the electricity supply side. Fragile grids in the region are struggling to keep the lights on, even with existing demand before electrification of vehicles, and therefore pose a substantial stumbling block to the mobility of electric vehicles.[10]

In a recent seminal publication on the topic, Collett and Hirmer[9] evaluated the readiness of paratransit in sub-Saharan Africa to transition to electric vehicles. They highlight the potential benefits of the shift, but identify the lack of data as the main impediment to making the transition a reality.[9]

Crucial knowledge gaps include the potential demand and where and when this demand will occur. We explore these questions provide some answers from our recent research.[11-14] We also highlight specific areas of remaining challenges and future research.

Background

Paratransit in Africa's developing countries differs substantially from that in developed countries. It operates somewhere between private passenger transport and conventional public transport in terms of cost, scheduling, routes and quality of service, and covers both urban and intercity travel.[15] This collective mode consists of shared-ride, demand-responsive privately owned vehicles such as the minibus taxis of Johannesburg, Lagos, Kampala and Nairobi or Kampala's motorcycle taxis ('boda bodas') and Nairobi's tricycle taxis ('tuk-tuks').[15-17] Unfortunately, they are notorious for poor safety and inefficiency.

Given its entrenched position in society, its economic gravity, and the political power of the multitude of taxi associations, MBTs are unlikely to be phased out anytime soon. However, the environmental cost of running them is worrying. It has triggered discussions about the possibilities of transitioning to electric minibus taxis (eMBTs) as part of the global electrification and sustainability agenda.[9,18]

In South Africa, between 250 000 and 300 000 MTB are spread across approximately 20 000 owners. Electric vehicle models indicate a power efficiency of approximately 1 kWh/km. Initial evaluations of current patterns have shown distances of approximately 200 km/day.[12] Electrifying the taxi industry will therefore add considerable strain to the grid, which raises the question: is our grid ready for this additional energy requirement? And do we have sufficient data to answer this question adequately?

The current grid in South Africa, run by parastatal behemoth Eskom, has an installed capacity of 48 GW, which reduces to 24 GW during regular breakdowns and maintenance programmes. With rolling regional blackouts (colloquially known as 'loadshedding') being a regular occurrence, instability and the lack of electrical supply present roadblocks on the highway to a future eMBT fleet. Eskom comprises 83% coal-based electricity generation. Thus, some researchers argue that deploying electric vehicles shifts gasoline usage and urban emissions to coal-fired power generation and rural emissions, in some cases exacerbating GHG emissions.[10,19] This is solvable by introducing smart charging strategies and renewable energy sources, especially in the region's sunny climate.[10,20,21] An accurate prediction of an eMBT fleet data set is thus of utmost importance to evaluate the impact of the transition.

Important stakeholders in this transition include those in charge of the vehicles, charging infrastructure, grid operators and electricity retailers, taxi owners and associations, and a plethora of governmental agencies. This complex web of agents needs to be convinced, not only of the importance of environmental sustainability, but also of financial viability.

Reliable and adequate data

In a recent publication, we assessed the energy requirements of the paratransit system from the perspectives of two mobility data collection methods: using handheld mobile devices, and using GPS devices fixed in the taxis.[11]

Passenger-based data

The first method, using the handheld mobile devices (often mobile phones) is commonly used by transport engineers in resource-constrained environments. This method involves fieldworkers boarding the minibus taxis as passengers and tracing the routes for the duration of the trip. An example of a compilation of such data we assessed is the 'Digital Matatu' data set, which was collected with mobile phones in Kampala, Uganda, and Nairobi, Kenya, and stored in the GTFS (general transit feed specification) format.[22,23]

Vehicle-based data

The second method, which is more invasive initially and has a higher set-up cost, uses vehicle-mounted GPS trackers. The trackers continuously log and transmit their location and velocity to remote data-collection centres through the communications network (usually cellular). Our data set consists of data from over a year of GPS vehicle tracking in Kampala, Uganda and in Stellenbosch, South Africa. These data are then made available from a cloud server either as timestamped GPS traces, or as processed timestamped trip information that captures the origin and destination.

Perspectives on energy and power results

Passenger-based data

The passenger-based energy results are shown in Figure 1. Figure 1a shows the aggregated results for Kampala, in which all the individual routes in the data set and their related frequencies were aggregated to estimate energy requirements for the paratransit system (minibus taxis only). The figure shows the power requirements throughout the day and the aggregated energy demand as the day progresses. Importantly, this includes only the routes covered in the data set, and no extrapolation was done to include other routes.

Figure 1b shows the aggregated results for Nairobi, again with all the routes and their corresponding frequencies aggregated for a system-level energy representation. The aggregated power profile is substantially lower than that of Kampala, which peaks at 280 MW, while Nairobi peaks at a mere 90 MW. This may be partly because Nairobi has fewer minibus taxis than Kampala. However, a simple proportional calculation shows that the difference may also be partly because of under-representation in the passenger-based acquisition of routes. It is a drawback of this method of data capture that we have no way of knowing the taxis' destinations unless they had passengers collecting data.

Vehicle-based data

The output of the eMBT simulation is shown in Figure 2 for Kampala and Stellenbosch. A clear typical temporal profile is apparent for the minibus taxis in both cities, closely matching the expected peak traffic hours. This profile indicates the energy requirements of the eMBTs, and already hints at some charging potential during the evening – probably from grid power – and some during the middle of the day – preferably from solar and wind power. It should be noted that the availability of these renewable sources are season, region, and weather dependent.

The mean instantaneous power demand profile of a working weekday in Kampala is shown in Figure 2a. 'Power demand' refers to the net power drawn from the vehicle's battery. The mean energy required per day was 220 kWh, and the mean distance was 224 km (obtained by integrating the power and speed profiles, respectively).

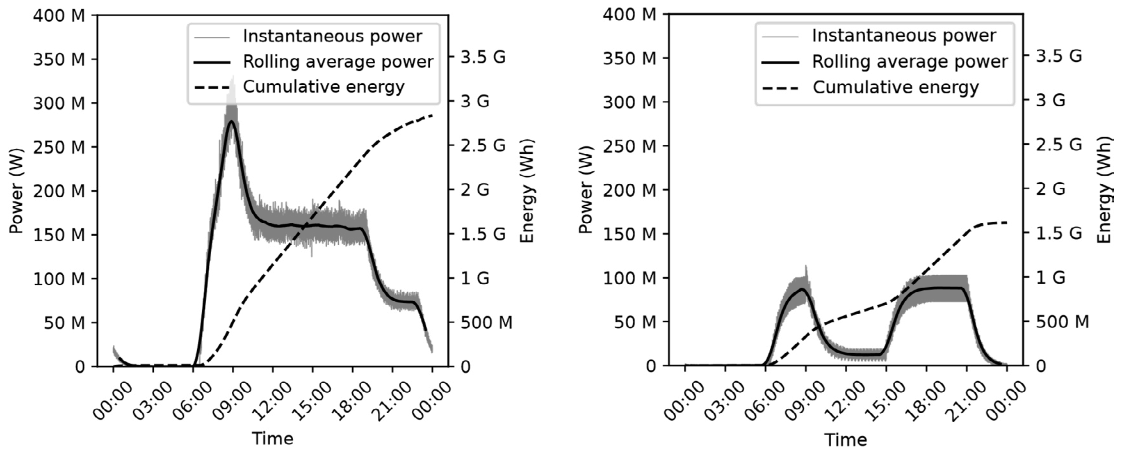
The mean instantaneous power demand for a working weekday in Stellenbosch is shown in Figure 2b. Not only is the profile clearly defined, but the variation between taxis, shown by the minimum and maximum profiles in the shaded area, is minimal. The only substantial deviation is the increase in the maximum profile just after 21:00. This is because some taxis start long-distance weekend trips on Friday evenings.[24] The mean energy required per day was 212 kWh, and the mean distance was 228 km.

The distribution of energy usage per day is shown in Figure 3a for each of the eight taxis in Kampala. Their energy usage is similar, with the median energy per taxi per day across all taxis ranging from 108 kWh to 335 kWh, with the mean of the medians equal to 220 kWh. The taxis travelled a mean distance of 224 km, leading to an energy efficiency of 0.98 kWh/km. The distribution of energy usage per taxi per day is shown in Figure 3b for the nine taxis in Stellenbosch. The taxis' energy usage is similar, with the median energy per day per taxi ranging from 189 kWh to 252 kWh, with the mean of the medians equal to 215 kWh.

The results show that a maximum usable battery capacity of approximately 500 kWh would be sufficient for urban travel, if charging is limited to the stationary period before the day's first trip, and, for 75% of the time, a 303-kWh battery would be sufficient. This indicates that the demand is much greater than the battery capacity of currently available passenger electric vehicles. To reduce the battery size and capital costs of the vehicle, it would be necessary for eMBTs to charge at various stops during the day, which could lead to a loss of potential revenue for the drivers.

Passenger versus vehicle data

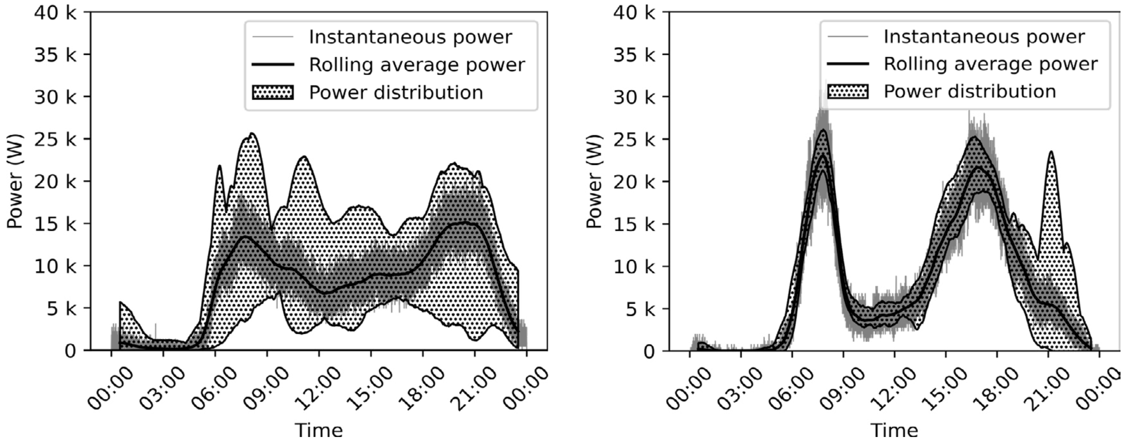
The Kampala profile from vehicle tracking in Figure 2 is substantially different from the passenger-based profile captured in Figure 1.



(a) Kampala

(b) Nairobi

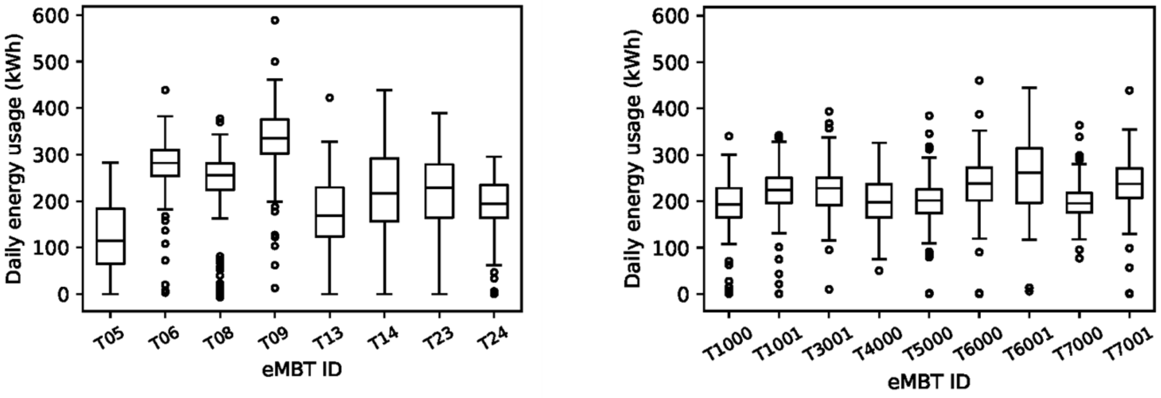
Figure 1: Daily power and energy profiles of minibus paratransit systems in Kampala and Nairobi, from passenger-based data.



(a) Kampala

(b) Stellenbosch

Figure 2: Summary of electrical demand for all the simulated electric minibus taxis' daily power (instantaneous and rolling average) sampled per second, expressed per taxi.



(a) Kampala

(b) Stellenbosch

Figure 3: Daily energy usage for each simulated electric minibus taxis (eMBT).

To illustrate the difference between the two data source methods, in Figure 4 we show Kampala's energy profile from the two vantage points. The overlay shows the passenger-based energy profile, which was down-scaled by the number of taxis in Kampala (25 000 according to Spooner et al.[25]), and our vehicle-based energy profile.

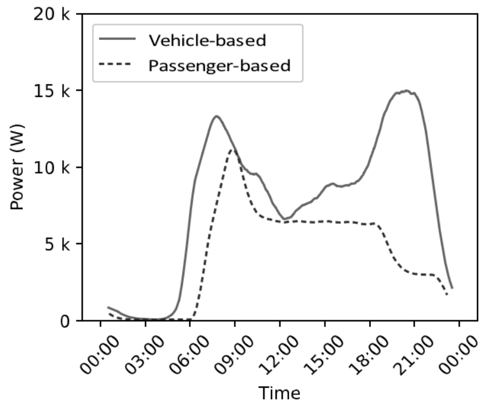


Figure 4: Comparison of Kampala per-vehicle power profiles derived from passenger-based and vehicle-based data.

The differences are stark. First, it is clear that the taxis started moving between 4:00 and 5:00, before the fieldworkers managed to get on board. Second, the passenger-based profile grinds to a halt just before supper time. But we know that the minibus taxis in our samples happily chug away until after 21:00.

Thus, although passenger-based data are readily available and often used, their usefulness in energy analyses is limited for several reasons:

- The data do not adequately reflect the mobility patterns from a vehicle perspective. They give information on a particular route's energy requirements, which is less useful.
- Fieldworkers will only track the MBT for a limited number of hours in a day, mostly according to normal office hours.
- Passenger waiting time, rather than vehicle waiting time, is captured with this method.

The vehicle-based method is much more useful for energy analysis than the first method, as it adequately and reliably captures the vehicle's moving and stopping patterns, which are very useful for energy analysis. Relying on the data captured by fieldworkers would therefore lead to a substantial error in energy estimations, exemplifying the crucial need for vehicle-based data collection. This adds weight to the statement by Collett and Hirmer[9] that stresses the need for adequate and reliable data.

Charging opportunities

To discover the eMBTs' opportunities and requirements if they are to charge during stationary periods, we did a 24-h analysis of the start times and the durations of stop events. The analysis shows what the average charger capacity should be if a vehicle is charged using only power from the local electrical grid. We applied a minimum stop duration of 20 min to ensure that only stops that are valid for charging would be identified and that drop or pick-up-and-go events were not included as charging opportunities.

Figure 5 shows the distribution across days of stop events with the minimum 20-min stop duration threshold applied. The Kampala scenario shows that each taxi's daily stop durations vary considerably. However, for both scenarios, the median stop duration does not vary much across taxis. The median duration per day ranges from 10 h to a maximum of 18 h for Kampala; that for Stellenbosch ranges from 15 h to 18 h.

To calculate the charger capacity, we used a relatively high energy demand and a relatively short charging time for an average demand situation. We used the average of the 75th percentile of the energy usage from Figure 3, and the average of the 25th percentile of the 24-h stop duration times from Figure 5. For Kampala, these were 273 kWh and 11.5 h, respectively, and resulted in a charger capacity of 24 kW. This calculation assumes a constant charging profile for the sake of simplicity, as a real electric vehicle charging profile would require additional modelling. With these assumptions, 23.7 kW for 11.5 h would fully recharge a taxi on most days. For Stellenbosch, these figures were 247 kWh and 15 h, respectively, resulting in a charger capacity of 16.5 kW.

Grid versus solar photovoltaic charging

We set up the System Advisor Model (SAM)-based photovoltaic (PV) model to calculate the energy available from PV sources and to study the daily charging potential for each eMBT in a synthetic fleet of nine eMBTs in Stellenbosch. Stop events were analysed to further assess the battery charging potential from solar PV by evaluating the times and duration thereof. These 'daily PV charging potentials' were aggregated for each taxi and plotted as box plots.

The complete inactivity observed between midnight and 5:00 for Kampala and between 23:00 and 5:00 for Stellenbosch indicates the best opportunity to charge from the grid. As this is a considerable amount of continuous time, charging can take place at low power to prolong battery life. But where are the taxis located during this time? The answer to this question could introduce new obstacles to the charging infrastructure.

Inactivity during the middle of the day provides the opportunity to charge from solar PV to reduce the load on the electrical grid and to reduce the size of the installed battery in the eMBT. The variation of charging potential between taxis is low, indicating that the taxis follow similar patterns during the daylight hours, and that they would require similar charging infrastructure.

After evaluating the needs of eMBT in Stellenbosch, approximately 320 m^2 of solar installation would be required per taxi to ensure its daily needs are met at least 50% of the time if no storage is used. Given the estimated 285 000 taxis in South Africa, our analysis indicates that to charge all the minibus taxis from the national grid will require 9.72% (61.27 GWh) of the current daily national installed (rather than operational) generation capacity. Reducing this strain with the use of solar PV is pivotal in the transition to eMBT.

Conclusion

The threat of climate change has propelled an energy revolution from vehicles with an internal combustion engine to electric vehicles in the Global North. Influenced by market forces and supplier preferences beyond its borders, this wave will eventually sweep across the Global South's organically evolved and notoriously chaotic paratransit systems and fragile electrical grids. In addition to the scarcity of electricity, the lack of data on the mobility of MBT poses a substantial challenge to these efforts.

We considered how the dissimilar mobility characteristics of minibus taxis will translate into electrical requirements. Also, because these vehicles park spontaneously at tacitly known stops of the drivers' choosing, for durations determined by passenger demand, the charging potential at these stops has hitherto been unknown.

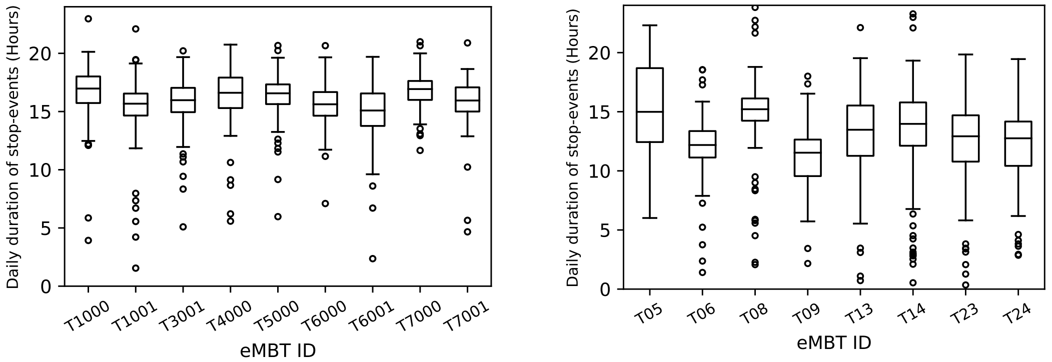
We found that passenger-based data may be useful for determining the aggregate energy load of a whole city or a single route. However, these results could be wholly incorrect if the passenger-based tracking is not reliable. On the contrary, vehicle-based tracking provides a reliable means of determining the energy requirements of a vehicle, and with sufficient adoption it could be used to determine system demand too.

Our results show that the electricity demand of the taxis was similar, with a nominal 250 kWh required per median day if no additional charging capacity is provided. This demand increased to 420 kWh when we included all days, except for one taxi, which required 490 kWh. The median stops per day ranged from 15 h to 18 h, suggesting considerable potential for charging.

Although these results are location specific, the models can easily be modified to suit the context of other developing countries.

The taxis with the shorter stopping periods, and hence the lower potential for charging, will need more energy because they are more mobile. Nevertheless, a nominal 24-kW charger will suffice when only charging only from the grid – if the grid is fully operational, which should not be taken for granted.

Given the constricted electricity production, the sustainability of future paratransit needs to be coupled with a transition to renewable energy. However, renewable sources are intermittent, and the output is not necessarily matched, in the time domain, to the load. It must therefore be matched by substantial investment in battery storage to decouple demand and supply temporally. This could take the form of stationary battery storage at charging stations or batteries used in swapping schemes. Stationary battery storage can be used to charge slowly from the grid or renewable sources when available – reducing the grid load – and can then be used to discharge faster into vehicles without burdening the grid. Batteries used for swapping can also charge slower from the grid or renewable sources when available – with a concomitant reduction on grid power load – and will probably be faster to swap than charging a vehicle with a fixed battery.



(a) Kampala

(b) Stellenbosch

Figure 5: Daily durations of minibus taxi stop events with a minimum duration threshold of 20 minutes.

Future work

Many challenges and unknowns remain in the transition to an electrified minibus taxi fleet. These can be classified as either on the vehicle’s demand side or on the electrical supply side.

We have answered the question of the vehicle’s energy requirements by simulation. However, these simulations were limited to an urban environment. But current internal combustion energy vehicles seamlessly transition to long-distance trips, which impose hitherto undetermined energy requirements for the vehicle. Moreover, the mobility analysis was performed with actual route way points, but with a micro-traffic simulation model that estimates energy efficiency – approximately 0.95 kWh/km – and which still needs to be validated with data from actual taxis in the region, captured at high temporal resolution (e.g. accelerometer or GPS).

On the supply side, many unknowns remain. These unknowns include the impact on mobility of the burden of loadshedding and the impact of electrifying on the low-voltage and medium-voltage distribution networks.

Fortunately, opportunities also lurk in the shadows. One such opportunity is the potential use of second-life vehicle batteries from developed countries in renewable powered charging stations. Another is the assessment of battery swapping schemes in the minibus taxi context, for both urban and long-distance travel to reduce stopping times.

Competing interests

We have no competing interests to declare.

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