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Using Solar PV and Stationary Storage to Buffer the Impact of Electric Minibus Charging in Grid-Constrained Sub-Saharan Africa

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Abstract: Despite the unstoppable global drive towards electric mobility, the electrification of sub-Saharan Africa's ubiquitous informal multi-passenger minibus taxis raises substantial concerns. This is due to a constrained electricity system, both in terms of generation capacity and distribution networks. Without careful planning and mitigation, the additional load of charging hundreds of thousands of electric minibus taxis during peak demand times could prove catastrophic. This paper assesses the impact of charging 202 of these taxis in Johannesburg, South Africa. The potential of using external stationary battery storage and solar PV generation is assessed to reduce both peak grid demand and total energy drawn from the grid. With the addition of stationary battery storage of an equivalent of 60 kWh/taxi and a solar plant of an equivalent of 9.45 kW_{pk}/taxi, the grid load impact is reduced by 66%, from 12 kW/taxi to 4 kW/taxi, and the daily grid energy by 58% from 87 kWh/taxi to 47 kWh/taxi. The country's dependence on coal to generate electricity, including the solar PV supply, also reduces greenhouse gas emissions by 58%.

Keywords: battery storage; electric minibus taxi; paratransit; PV; solar power; grid impact

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1. Introduction

The drive for scaled electric mobility has increased exponentially in the Global North over the past decade. However, in sub-Saharan Africa, this campaign is overshadowed by a severely restricted electricity system in terms of immediate power delivery and cumulative energy required. To soften the blow to the grid, this paper proposes stationary external batteries at minibus taxi terminals to reduce peak power demand on the grid and solar rooftop PV to reduce the total energy demand from the grid, thereby increasing the sustainability of electric transport in the region. A novel grid-impact simulator is developed and presented to assess the impact of the abovementioned interventions.

Sub-Saharan Africa's so-called "paratransit", artisanal or informal public transport, differs substantially from paratransit in developed countries in its vehicle type and operations. Developed countries define it as a point-to-point, flexible, demand-responsive transport service customised with special requirements for older people and people with disabilities. However, in the African context, the word refers to the mode of mobility for the vast majority [1–3]. Sub-Saharan Africa is largely dependent on its paratransit network for providing transport, as it transports more than 70% of daily commuters [4] with approximately 250,000 taxis in South Africa alone [5]. It is a source of livelihood for many families [4], and a country's economic and social development depends mainly on the existing transport sector [6]. Its operation is characterised by falling between a private passenger transport and a conventional public transport system in terms of cost, scheduling, routes and quality of service [7].

The region's paratransit industry consists mainly of vehicles known as minibus taxis (MBTs), as shown in Figure 1. Paratransit in Johannesburg, Lagos, Kampala and Dar es Salaam account for approximately 70%, 90%, 91% and 98% of the road-based public trips, respectively, with 83% of these paratransit trips conducted by MBTs [4,8]. These MBTs are exclusively powered by internal combustion engines (ICE) and, as a result, contribute towards the emission of greenhouse gasses (GHG) and a general decline of air quality in African cities [9]. Furthermore, MBTs' contribution to urban air pollution is a result of the MBTs being old (often older than 20 years), thus fuel inefficient, and idling for long periods of the day [10,11]. The World Health Organisation classifies exposure to ambient air pollution as a significant threat to human health in sub-Saharan Africa and has also linked it to the increase in cardiopulmonary and cardiovascular diseases as well as lung cancer and respiratory infections [10,12]. In addition to GHG emissions (such as CO_2, CH_4, and HFC [13]), the use of vehicles also contributes to pollution. ICE vehicle pollutants include nitrogen oxides (NO and NO_2, or NO_x), carbon monoxide (CO), volatile organic compounds (also known as hydrocarbons or non-methane hydrocarbons), and particulate matter (PM2.5 and PM10) [14]. With the advent of electric mobility, these hazardous pollutants are moved out of the urban environments where mobility occurs, to where electricity is generated. In the event of offsetting the energy with renewable sources, the pollution is proportionally negated.

Figure 1. Minibus taxis, the mainstay of transport in sub-Saharan Africa.

Although many have called for a total overhaul of the MBT industry, it is well entrenched within society. With its market dominance and agility in the informal townships (a term used to describe informal settlements similar to Favelas in Brazil), it is unlikely to be phased out as the preferred mode of transport soon, necessitating its electrification [9].

The fact remains that developing low-carbon transport in cities is crucial to the global agenda. Three of the seventeen United Nations Sustainable Development Goals are clean energy, sustainable cities and climate action (goals one, eleven and thirteen, respectively) [15]. Consequently, electrification is promoted as a low-carbon transport strategy to slow down climate change and reduce carbon emissions [6,16]. This transition from ICE vehicles to electric vehicles (EVs) is gradually picking up in developing countries [17], while many global vehicle manufacturers are planning to stop production of ICE vehicles as early as 2030 [18]. Sub-Saharan Africa is already seeing a few isolated cases of electric mobility with the main focus on micro-mobility (tricycles and motorcycles), busses and cars [17].

Research from outside the region has demonstrated that EVs are generally three times more efficient than ICE vehicles and twice as efficient as hybrid vehicles [19,20]. Although there is no debate regarding their efficiencies, discussions continue on EVs' economic and environmental trade-offs. Even though there is evidence of sustainable EV deployment, some researchers argue that EVs shift gasoline usage to coal-fired power generation, which exacerbates CO_2 emissions by the power systems [21]. This uncertainty is overshadowed by the looming threat of energy scarcity on the electricity supply side to meet the demand for EVs. Sub-Saharan Africa already has fragile grids struggling to keep the lights on, even with the existing load, Ref. [22] which will be exacerbated by transformer overloading and power quality degradation, in voltage and frequency, resulting in significant power losses [16,23].

To address the challenge of charging the multitude of eventual electric minibus taxis on sub-Saharan Africa's frail electrical networks, this paper:

- Proposes the integration of two elements at the minibus taxi stations:
  - Solar PV plants to utilise the abundant insolation in the region;
  - Stationary battery storage to both buffer the load on the grid and maximise solar utilisation,
- Determines the per-taxi sizes of stationary battery storage and solar PV plants that optimise solar utilisation and grid load reduction.

To conduct this, we used our published (not new) simulation package, Grid-Sim [24] to determine the resulting impact on the electrical grid. The proposed setup is shown in Figure 2.

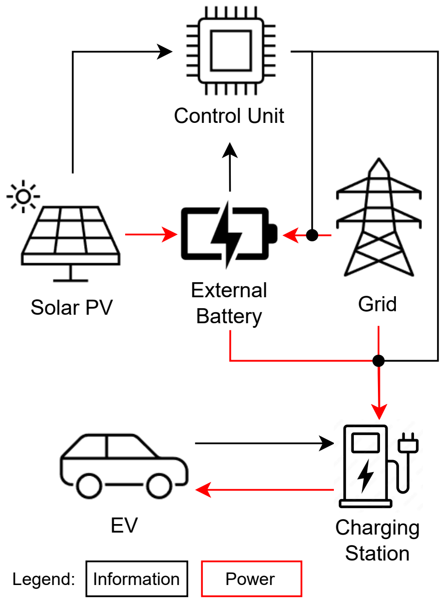


Figure 2. Proposed charging setup.

2. Literature Review

The integration of PV and external batteries is by no means a novel concept. However, the contribution of this study rather focuses on the importance of scenario-specific sizing when it comes to these entities. In addition, the importance of sizing is also shown in a South African paratransit context, where the majority of vehicles operate in unison, creating notable obstacles for immediate power supply.

In the context of this paper, we specifically look at the current electrical grid situation in South Africa. The existing grid in South Africa is run by Eskom, which has an installed capacity of 50 GW. However, the available capacity frequently reduces to 25 GW due to regular breakdowns and maintenance programmes. This has resulted in rolling regional blackouts, colloquially termed "loadshedding", being a common occurrence in the country [22,25]. Due to Eskom's reliance on coal power [26], research has stated that the deployment of EVs may increase the emission of greenhouse gasses into the environment [21].

2.1. Grid Impact of EV Charging

The utility grid can be affected negatively by private EVs that charge either at public charging stations or at home and charge unscheduled. Specifically, the distribution grid [27,28]. The same logic then follows through to the electrification of minibus taxis. Thus, the development of EV charging structures with minimal impact on the existing utility grid is required [12]. This is further substantiated by Abraham et al. [17], who states that if a large enough fleet is used, a substantial burden would be placed on the local electrical distribution network of the countries in sub-Saharan Africa due to charging.

Currently, three different EV charging strategies are being utilised: charging posts, fast charging stations (FCS) and battery swap stations [29]. It was already stated in [30] that the battery swapping method is not a viable solution for the electric taxi fleet, as it would strain the original equipment manufacturers (OEMs) to produce this technology when significant other technology already exists. For charging posts and FCSs, the charging power for EVs can be categorised into various classes and power levels [31]. The first is known as slow charging [31], which consists of AC charging at Level 1 ranging from 1.4 to 2.2 kW [12,32,33]. The second is known as accelerated charging [33], which consists of 3 to 7.4 kW for single-phase [34], or 11 to 22 kW [12,32,33] for three-phase AC charging. The final one is known as fast charging [31], which consists of DC charging at Level 3, which ranges anywhere from 50 to 350 kW [31–33]. AC charging requires an onboard power converter, while DC charging stations have an external power converter [31,33].

The main grid components affected by the implementation of EV chargers are the transformers, transmission lines, and switchgear protective devices [12]. As the number of EV chargers connected to the grid increases, the load on the utility also increases. This issue is significantly more pronounced for poorly maintained utility grids [12], as is the case for most sub-Saharan countries. Mitigation strategies are, therefore, needed to reduce the impact on the grid. These mitigation strategies include:

- Vehicle-to-grid (V2G) implementation: Employs the use of EVs to feed unused power back into the grid for grid stabilisation purposes [35–37].
- Smart charging strategies: Control the charging speed and time frame when EVs can charge to reduce loads during peak times [37,38].
- Stationary battery energy storage systems (BESSs): Help offset the charging in peak times [37,39].
- Renewable energy sources (RES): Reduce grid impact and increase sustainability [12].

This paper will assess BESSs and RES for implementation at multiple taxi ranks. The grid can charge the stationary BESSs during off-peak times or can be charged with the use of RES, such as solar PV panels [40].

2.2. External Battery Storage And Renewable Energy Integration

Introducing renewable energies into the grid can help meet the demand and reduce emissions [41,42]. Furthermore, studies have shown that the incorporation of renewable energy sources into the grid enhances the power quality of the grid without any negative impact on the grid [12,43–45].

Opportunities for large-scale PV installations in populated areas are limited to rooftops due to the lack of land [46]. The amount of energy produced from solar panels is further limited by their size, number, sunlight irradiance and direction/angle [46]. Like many countries in sub-Saharan Africa, South Africa has high levels of solar energy. Approximately 4.5 to 6.5 kWh/m^2 of solar energy is experienced on average per day [17,47]. This is much more than London, with 0.5 to 4.7 kWh/m^2 [48] and New York, with 3.0 to 5.7 kWh/m^2 [49]. This makes using solar energy for grid support in localised areas viable.

Furthermore, installing grid-integrated storage systems represents an alternative means to reinforce the grid [37]. This is achieved because these batteries can charge slowly from the grid or renewable sources when available. These batteries can also be used for fast charging the EVs without burdening the grid [40,50], or for providing ancillary services for the grid [31]. An investigation of existing grid simulators is thus required.

2.3. Existing Grid-Impact Simulators

Various studies have been conducted to investigate the effects of EVs on the electrical distribution network [28,29,51,52]. Certain parameters were investigated, such as a varying size of EV penetration into the market [51] or scheduled versus unscheduled charging [28,52], or the effect of charging locations and infrastructure [29], as a way to determine the impacts that EV charging has on power quality and power consumption. These studies all present a general overview of the effects of EVs on the grid. However, specific studies have been conducted on integrating BESSs and renewable sources into the grid.

For example, Bartolucci et al. [53] investigated using stationary BESSs, solar charging and a grid connection for charging EVs. However, the focus was to minimise the charging process's carbon emissions and maximise local energy production using first-life and second-life batteries. A similar approach was taken by Bracco et al. [54], where instead of investigating second-life batteries, V2G was incorporated with the stationary BESSs. A method for coordinated control of multiple BESSs located at various charging parks was presented by Kucevic et al. [37]. However, the BESSs presented were merely meant to provide grid support and not to facilitate EV charging but were instead introduced as a result of the EVs. A similar approach was taken by Eid et al. [55], which also aimed to optimise the control of the energy storage systems. However, these energy storage systems were located at the renewable energy generation sites, not at the charging station points. The BESSs served to smooth the integration of renewable sources into the grid and lessen the grid impact. The BESSs only provided grid support and did not charge the EVs.

Another investigation was conducted by Krim et al. [56] using solar panels, stationary BESSs and a grid connection. They aimed to determine the preliminary requirements for such a system to avoid overloading the grid. They found that with slow charging, EVs could be charged mainly with PV and the stationary storage system. Fast charging of EVs was found to be primarily taken from the grid. Another investigation into fast charging was given by Shariff et al. [45] who found that two 48 kW chargers could be used to operate the system in isolation. Funke et al. [50] aimed to investigate using BESSs for intraday electricity trading.

Moreover, specific case studies have been presented in the literature on these scenarios of incorporating BESSs, renewable sources and a grid connection. A survey by Fakour et al. [46] investigated the integration of a solar carport canopy for charging EVs in Kaohsiung City, Taiwan. The test was run without a grid connection and battery storage. However, it was concluded that a grid connection and sizeable BESSs would be required to ensure sufficient charging.

The study presented by Girard et al. [57] aimed to give a second life to their taxis in Chile by converting them to EVs. Similarly, an investigation was conducted to determine the impacts of charging when a PV system was installed. However, they stated that future studies would need to be made to limit the solar power generation intermittency. This can be solved by introducing BESSs. They also found that converting taxis to EVs would only be beneficial if they were charged with renewable energy due to Chile's significant reliance on coal power for generation, similar to the case in South Africa.

Another example is presented by Park et al. [58] where Daejeon City, South Korea, aims to convert its taxi fleets to EVs. The aim was to incorporate renewable power sources into the system. An initial phase of EVs was introduced, and an investigation was conducted to determine the impact that 10 and 100 EVs would have on the grid in phases two and three, respectively. Even the process proposed by Bartolucci et al. [53] was applied to a parking lot in Rome.

All of these studies presented various methods for obtaining the necessary data. Dang et al. [28] received their data from charging profile observations of already in-circulation EVs provided by their advanced metering systems. Verzijlbergh et al. [52] used Dutch driving patterns to help determine the charging behaviour. Liu et al. [29] obtained the charging profile for their EV fleet from current daily car travel behaviour in Beijing. Furthermore, the mobility behaviour for private vehicles in Germany was used in assessing the grid impacts in [50].

The data used for the EVs in [55] were based on the National Household Travel Survey. Data were further collected in [58] using the charging data of already operational electric taxis, in this case, the "SM3ZE", an EV developed by Renault. The data used in [46] for the investigation of the carport were based on the entry and exit times of vehicles exiting the carport.

It is clear from the literature presented above that there is a gap in determining the impact electric taxis will have on the grid in an already fragile grid system. This can be seen by the fact that minimal investigation is conducted for public transportation sectors, and if conducted, does not apply to the minibus taxis in sub-Saharan Africa, as can be seen in the Nissan V16s of Chile [57] and the SM3ZE of Daejeon [58]. This paper aims to fill in these gaps and provide a possible solution to the negative grid impacts that the electrification of minibus taxis will hold.

3. Methodology

This section provides a detailed description of the novel software simulation tool developed. Furthermore, we also present the input data used for implementing Grid-Sim in a test use case.

The flow diagram in Figure 3 shows the process on a low level. This also outlines the material discussed in this section, as each block in the flow diagram has a corresponding subsection.

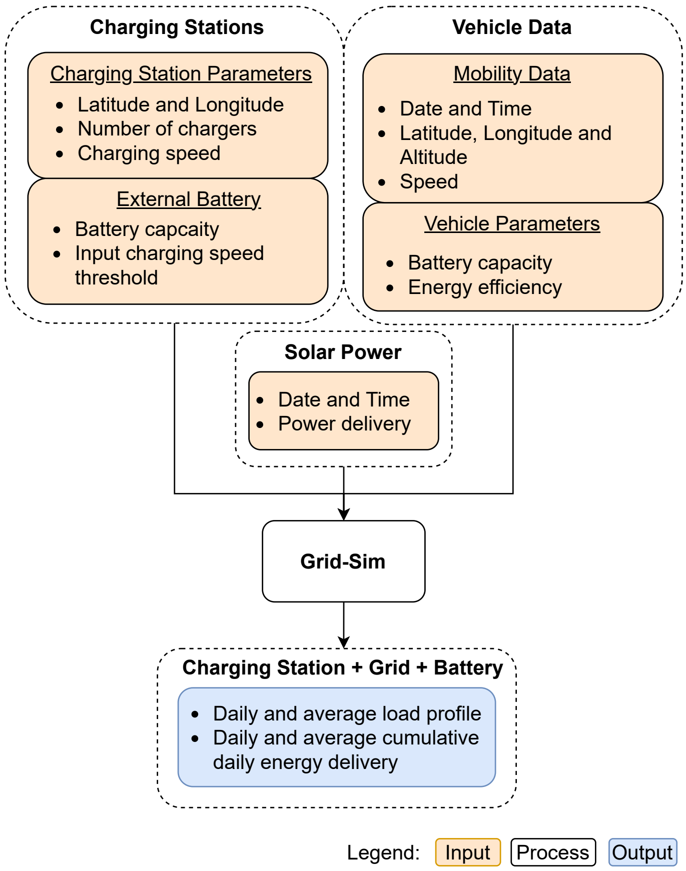


Figure 3. Low level of the process followed in this paper.

3.1. Grid-Sim

As there were no available operational data on electric minibus taxis in sub-Saharan Africa, a software simulation tool was required to simulate the grid impact of the charging. A tool called Grid-Sim was developed for this purpose [24].

Due to limited data availability, the tool must have the least possible input requirements. As a minimum, Grid-Sim only requires vehicular data (vehicle parameters and mobility data) and charging station parameters. In the context of this study, additional input data regarding the external battery and solar PV installation are required. The exact parameters used for each input entity in this paper are stated in Section 3.2.

It is important to note that Grid-Sim is not an electric vehicle mobility simulator or charging station optimisation software. It requires realistic mobility data for an EV to achieve, coupled with a sufficient charging station infrastructure. If these expectations are not met, the simulation cannot run successfully.

Grid-Sim starts by using the mobility data and vehicular parameters to calculate the power offtake (energy used from the battery) for each minute of the simulation period. After that, the battery state of charge (SOC) is continuously updated per minute using the power-offtake and charging station parameters. Finally, the power source supplied to the taxi by the charging station is defined as directly from the grid or the external battery.

The internal process of how Grid-Sim simulates electric vehicle charging is extensively covered in a dedicated paper by Giliomee et al. [24]. In the context of this study, the source of the power supplied by the charging station to the vehicle is further analysed.

The external battery's charge and discharge can be determined once the power draw from the charging station to the vehicle is defined. To do this, we analyse each charging station individually. The power mix between the solar PV, grid, and external battery is determined as follows.

The external battery has a defined input charging threshold. This parameter, adjustable to the user, ensures that the external battery always charges at a minimum rate. If the power delivered by the solar PV is less than this threshold, the difference in power will be drawn from the grid to meet the threshold. However, exceptions to this are if the external battery has a SOC of >85% or the grid is already directly charging a vehicle. In both these instances, the external battery will solely charge from solar PV. By limiting the grid-drawn power for external battery charging up to a specified SOC, we ensure enough overhead capacity remains for the external battery to utilise the morning solar supply. The vehicle will only charge from the grid if the external battery's SOC is <20%. Otherwise, the vehicle will solely charge from the external battery.

Both the parameters above are also adjustable to the user.

3.2. Input Data

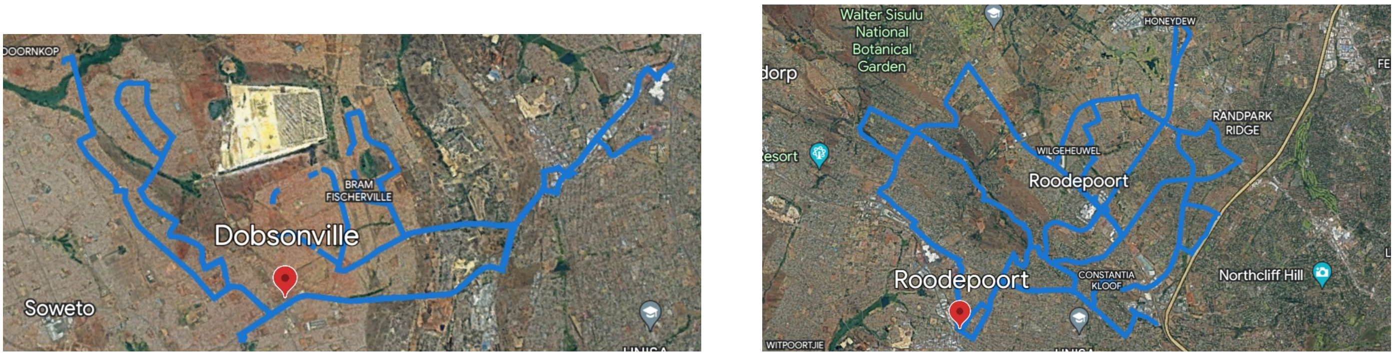
As stated in Section 3.1, the simulation tool requires mobility data from EVs as input. However, there are currently no mobility data from electric taxis operating in sub-Saharan Africa. Thus, an operational plan specifically designed for the electric taxis is needed. An operational plan for a fleet of minibus taxis developed by the World Bank was used in this study [59]. The operational plan was derived from tracking data from an existing active route with ICE vehicles in Johannesburg, South Africa. This dataset was optimised to meet current passenger demand while reducing the number of taxis required to do so to improve vehicle productivity rather than focusing on electrification. This reduced the required number of vehicles from approximately 800 to 202 while serving the same demand. The **Dobsonville taxi rank** and Taxi Rank 5 (opposite Roodepoort Railway Station—simply referred to **Roodepoort taxi rank** from here onward) were identified and chosen as charging stations.

Each taxi rank, along the route driven by the taxis it serves, is shown in Figure 4.

The operational dataset contains origin and destination data of the various journeys during a day's operation for each taxi. The parameters in this dataset include:

- Start and end location of each journey
- Start and end time of each journey
- Distance travelled between locations

As this is an origin and destination dataset, no speed information was given. The operational plan was transformed into a mobility dataset, similar to GPS traces, to serve as input to Grid-Sim. This involves separating each journey's start and end locations into two separate data points, replacing the name of each site with GPS coordinates, and adding the speed as zero for each input sample.



(**a**) Dobsonville, Johannesburg, South Africa (**b**) Roodepoort, Johannesburg, South Africa

Figure 4. Taxi ranks along with the routes it serves.

For this paper, only weekday operations were considered. Operational data from weekends are completely removed to ensure a realistic recharging time window for the external batteries from Friday evenings to Monday mornings. The Dobsonville charging station serves 114 electric taxis in this working plan, and Roodepoort serves 88 weekly. On average, an electric cab travels 143 km/d in this operational plan.

As the operational plan for each weekday is identical, the same grid impact will be seen throughout the year for the grid-only charging scenario. However, with the addition of solar PV power supply, the change in solar irradiance over each season will have a noticeable effect on the subsequent grid power draw. Thus, the data are extrapolated and assessed for the best, worst and two intermediate months according to solar irradiance. For the region considered in this paper, the months are chosen as January (best), May (worst), August (intermediate) and November (middle). The reader is reminded that the region follows the southern hemispheric seasons.

A suitable electric minibus taxi and charging station parameters were chosen to optimise the operational model for an electric vehicle. This is further discussed in Sections 3.2.1 and 3.2.2, respectively.

3.2.1. Vehicle Data

A minibus with a nominal 100 kWh battery capacity was used with a usable capacity of 80%.

The energy efficiencies for minibus taxis in literature and manufacturer specifications range from 0.26 kWh/km to 0.93 kWh/km [60–63]. However, as energy efficiency is driving style dependent, an efficiency representative of the South African minibus industry is needed for this paper. One such study has found an energy efficiency of 0.55 kWh/km, which will be used in this paper [64].

Although the mobility data are required as part of the *Vehicle Data* input, it has already been discussed in Section 3.2. This is because it plays a vital role in all other design choices and input datasets required for the use case analysis in this paper.

3.2.2. Charging Stations

As part of the input dataset previously discussed, two taxi ranks are given as charging stations, namely Dobsonville and Roodepoort. The operational data show that a single taxi only goes to one or the other taxi rank.

The number of chargers at each taxi rank and the charging speed thereof have already been defined in the input dataset. Each taxi rank is specified to have 56 charging outlets, each with an AC charging speed of 22 kW. This is sufficient for a midday recharge for afternoon operations and an evening recharge to prepare for the following morning's peak operational demand.

Several external battery capacities were chosen to be simulated in this paper. This allows for assessing the change in grid impact as the external battery capacity changes.

The external battery capacity iterations were chosen according to the number of electric taxis charging at each taxi rank and an electric taxi's battery capacity. Increments of 10% were chosen, where the battery capacity of an electric taxi is 100 kWh as previously stated. Thus, Dobsonville has external battery increments of 1140 kWh for its 114 taxis, whereas Roodepoort has 880 kWh increments for its 88 taxis.

Each external battery's input charging speed threshold at a taxi rank is chosen as 350 kW, which is selected according to the fastest current publicly available DC charger on the market. Thus, if the power supplied by the solar PV is less than 350 kW, the grid will assist in providing the difference in ability.

Each taxi rank's physical location will serve as input for the solar PV sizing, which is further discussed in Section 3.2.3.

3.2.3. Solar Power

The sizing of the solar PV installations is limited by the physical surface area available at each taxi rank. The open surface area is separated into two scenarios according to the current available roof space on taxi-rank buildings or the total surface area of the taxi rank. The scenarios are, respectively, defined as Roof Area Solar and Total Area Solar.

The surface area available in each scenario at each taxi rank varies significantly. At Dobsonville, the available roof space is 468 m^2 (4 m^2/taxi), where the total area is 1888 m^2 (17 m^2/taxi). In contrast, the Roodepoort rank covers a larger area and serves fewer taxis. Here, the available roof space is 1355 m^2 (15 m^2/taxi), where the total area is 4093 (47 m^2/taxi)

The PV sizings are as follows according to the available area at each taxi rank in each scenario. At Dobsonville, the roof area scenario has a 47.25 kW_{pk} (414 W_{pk}/taxi) solar plant, and the total area scenario allows for a 128.7 kW_{pk} (1129 W_{pk}/taxi) solar plant. The larger area at Roodepoort allows for 141.75 kW_{pk} (1610 W_{pk}/taxi) roof area and 207.9 kW_{pk} (2362 W_{pk}/taxi) total area installations, respectively. All PV installations use the same 450 W solar panel [65].

In addition to the system sizing, weather files of the chosen locations are also required. For the area assessed in this paper, the newest publicly available weather files from the National Renewable Energy Laboratory [66] are from 2019. System Advisor Model (SAM version 2021.12.2 r2) [67] is used to simulate the energy generated from each solar PV installation.

Power outputs from SAM are given in 30 min increments for each date in 2019. As the grid impact is assessed on a per-minute base in Grid-Sim, each output sample will be extrapolated to deliver the same power for the entire 30 min period.

4. Results

Analysis of the grid-impact results starts by defining the grid-only charging reference scenario using the homogenous optimised schedule described in Section 3.2. In this case, the reference scenario is a charging station without the inclusion of external stationary batteries or solar installations. The daily load demand profile for the reference scenario is shown in Figure 5, with the average cumulative daily energy drawn from the grid shown in Table 1.

Table 1. Daily cumulative energy drawn from the grid for each taxi rank without external batteries or solar installations.

Taxi Rank	Energy [kWh]
Dobsonville	9959
Roodepoort	7680

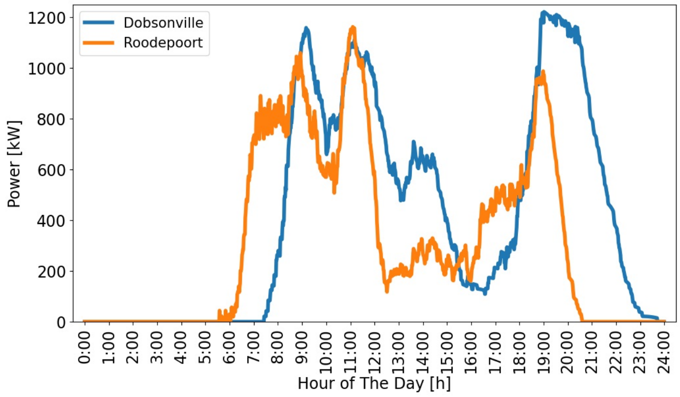


Figure 5. Grid load demand profile per taxi rank for 22 kW charging without external batteries or solar installations.

By averaging these results per taxi at each taxi rank, we approximate a peak load of 10.7 kW/taxi and an energy requirement of 87.4 kWh/taxi/day at Dobsonville and a peak load of 13.2 kW/taxi and an energy requirement of 87.3 kWh/taxi/day at Roodepoort.

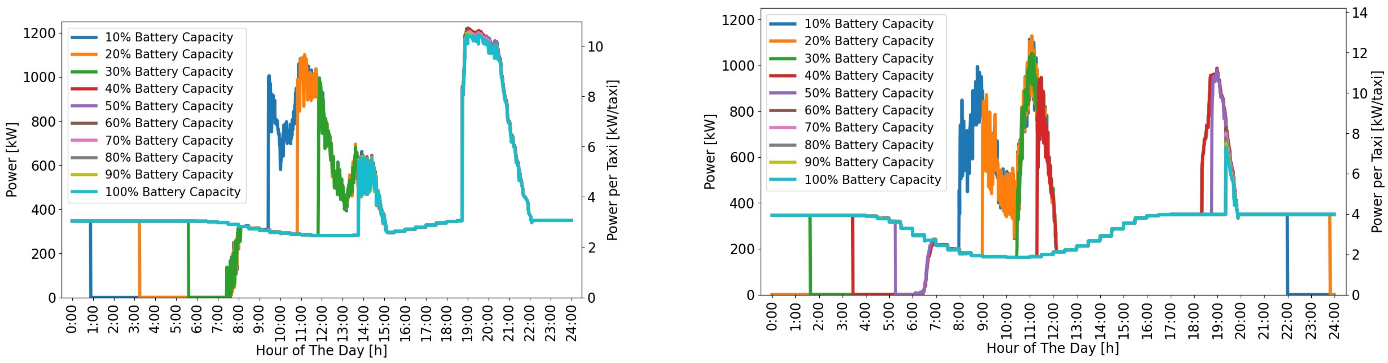
This section will discuss the results from each taxi rank individually. This addresses the solar irradiance, the total area available for solar installations, and the number of taxis at each rank independently.

4.1. Roof-Area Solar for Different Battery Sizes

This section gives results from the scenario of available roof space solar installation. This scenario is when the current general roof area at each taxi rank is utilised for the solar installation to supply power to the external battery.

For the available area and solar PV installation specifications defined in Section 3.2.2, a yearly energy yield of 189,620 kWh and 489,767 kWh is generated from Dobsonville and Roodepoort, respectively. This results in 4.55 kWh/taxi/day solar energy available at Dobsonville and 15.25 kWh/taxi/day at the Roodepoort taxi rank. As this yield only equates to 5% and 17% of the daily requirement at Dobsonville and Roodepoort, respectively, the sustainability impact of this supply is minimal. Further sustainability analysis is conducted in Section 4.2, where a larger solar PV installation is specified.

Figure 6 shows the grid-load profile for each taxi rank for each external battery capacity increment with solar installed on the available roof space.



(**a**) Dobsonville (**b**) Roodepoort

Figure 6. Average grid load profiles for each battery capacity iteration for available roof area solar installation.

In the power graphs presented in Figures 6 and 7, a power draw of ≥350 kW indicates the inability of the external battery to supply power to the taxi due to its energy being depleted. Thus, the required power for charging is provided from a grid connection.

In contrast, a grid load demand of ≤350 kW indicates that the taxi charges from the external battery.

From Figure 6a, it is seen that the **Dobsonville** taxi rank requires at least a 40% external battery capacity to supply the midday demand. However, no external battery capacity is large enough to sufficiently provide the demand for the early afternoon (14:00). The reason for this apparent ceiling of 40% is the recharging rate of the external battery. Moreover, the lack of any battery capacity significantly reducing the evening load demand on the grid is also due to the battery's charge rate rather than its ability. These issues will be examined further with the help of the external battery average state of charge profile presented in Figure 8a.

Figure 6b shows that an external battery capacity of 50% is required at **Roodepoort** to reduce the midday peak grid demand to only the charging threshold of the external battery. However, as with Dobsonville, no battery capacity is large enough to decrease the evening peak demand to only the external battery recharging threshold.

The minimal impact of the solar power delivery at Dobsonville can be seen in Figure 6a, where a near-constant base power of 350 kW is drawn from the grid. During peak solar power delivery, the grid power draw only reduces by 20% to 280 kW. In contrast, the more extensive roof area solar installation at Roodepoort reduces the grid power draw by 54% to 162 kW during the peak solar power delivery time.

The average cumulative daily energy drawn from the grid for each taxi rank is shown in Table 2.

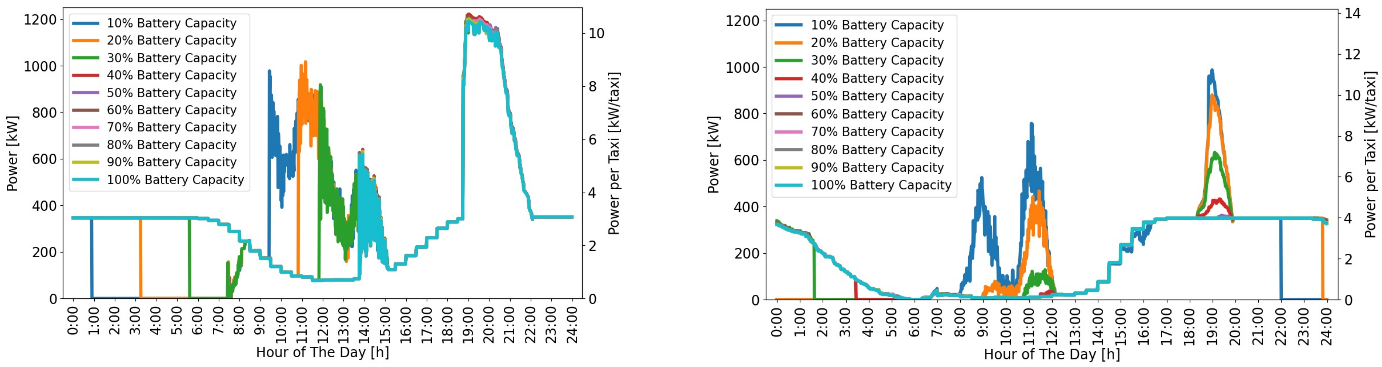
Table 2. Average daily cumulative energy drawn from the grid for each battery capacity iteration for available roof area solar installation.

Battery Capacity Increment [%]	Energy [kWh] (per Taxi) Dobsonville	Roodepoort
0 [Reference]	9959 (87.4)	7680 (87.3)
10	9767 (85.7)	6722 (76.4)
20	9876 (86.6)	6796 (77.2)
30	9973 (87.5)	6868 (78.0)
40	10,085 (88.5)	6934 (78.8)
50	10,075 (88.3)	7013 (79.7)
60	10,065 (88.3)	7062 (80.3)
70	10,055 (88.2)	7055 (80.2)
80	10,045 (88.1)	7048 (80.1)
90	10,036 (88.0)	7041 (80.0)
100	10,026 (87.9)	7034 (79.9)

As expected, the solar energy supply does not have a noticeable impact on the energy grid supply for the **Dobsonville** taxi rank. The lack of this impact is due to the relatively small ratio of area available for solar installations per taxi. An average increase in energy drawn from the grid across all battery capacity iterations of 0.4% is seen, with an effective solar plant of $4\,\mathrm{m}^2/\mathrm{taxi}$ ($0.83\ \mathrm{kW_{pk}}/\mathrm{taxi}$). This is due to the additional energy drawn from the grid to recharge the external battery.

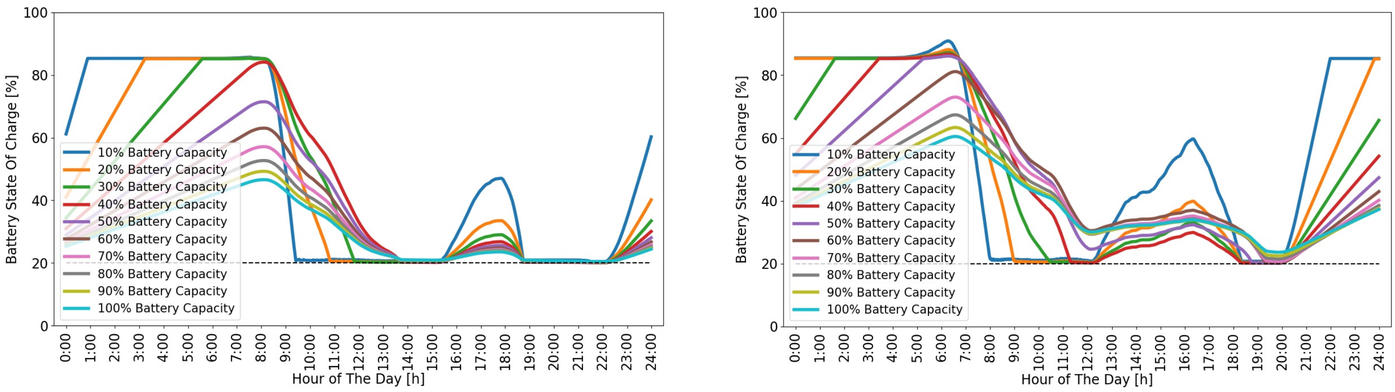
In contrast, the larger solar area to taxi ratio at **Roodepoort** taxi rank has a noticeable impact on the results, which show a 9.4% reduction in grid energy across all battery capacity iterations, with an effective solar plan of $15\,\mathrm{m}^2/\mathrm{taxi}$ ($4.39\ \mathrm{kW_{pk}}/\mathrm{taxi}$). However, the specific grid energy demand varies across all battery capacity iterations and does not monotonically increase or decrease as the external battery capacity increases. This is mainly affected by the level of battery utilisation and the related temporal dependence on solar generation.

As anticipated, Figure 8a shows that no battery capacity iteration for **Dobsonville** has adequate time to recharge after the afternoon peak to supply the evening demand. This raises the question of whether variable input charging speeds, optimised for the rank-specific demand profile, would be beneficial. This is further discussed in Section 5.



(**a**) Dobsonville (**b**) Roodepoort

Figure 7. Average grid load profiles for each battery capacity iteration for full taxi rank area solar installation.



(**a**) Dobsonville (**b**) Roodepoort

Figure 8. External battery state of charge for each battery capacity iteration for available roof area solar installation.

Furthermore, Figure 8b confirms that a battery capacity of ≥50% is sufficient to supply the midday peak. Although the more significant battery capacity iterations do not deplete to the minimum of 20% during the evening peak, the demand for a single sample [minute] exceeds the energy available by over 20%. Thus, Grid-Sim does not allow charging from the external battery for this sample, and power is drawn from the grid. Consequently, the battery state of charge remains slightly over 20% during this time, as observed between 19:00 and 20:00.

As mentioned, no battery capacity iteration can fully supply the evening demand. Concluding the afternoon peak, most batteries' state of charge only replenishes to 25% to 35%. Thus, the lack of supply for the evening peak demand can be attributed to the lack of recharging during the afternoon rather than the actual battery capacity.

Also seen in Figure 8a,b, is that the grid charging threshold of 85% proves to be sufficient as there is enough battery capacity left for the early morning solar energy to charge the battery further. However, this will be re-assessed for the larger total taxi rank area solar installation scenario.

4.2. Total Area Solar

This section gives results from the scenario where the entire taxi rank area is used for solar PV installation.

For the solar PV installation sized in Section 3.2.2, a yearly energy yield of 759,140 kWh is generated at Dobsonville, with 1,536,354 kWh at the Roodepoort taxi rank. This results in solar energy of 18.6 kWh/taxi/day and 47.8 kWh/taxi/day for Dobsonville and Roodepoort, respectively. Although the solar energy generated at Dobsonville in this scenario is four times more than in the Roof Solar scenario, the daily energy yield is still only a mere 21% of what is required, given a solar plant of 17 m^2/taxi (2.49 kW_{pk}/taxi). However, the solar energy yielded at Roodepoort now equates to 55% of the daily requirement, given a solar plant of 47 m^2/taxi (9.45 kW_{pk}/taxi). We thus, expect to see a significant reduction in grid-drawn energy at this charging station. This is further examined in Table 3.

Figure 7 shows the grid-load profile for each taxi rank for each external battery capacity increment.

Figure 7a shows that no battery capacity iteration is big enough to fully supply either the full midday or evening peak demand at **Dobsonville**. Although a reduced grid load is seen during the midday, thanks to the larger solar PV installation, this design's low recharging rate remains a shortfall. This is further discussed in Section 5.

However, results from Figure 7 indicate successful battery capacity iterations for the entire peak demand supply at **Roodepoort**. With the increased solar PV supply, grid-drawn energy is near zero for battery capacity iterations of ≥30% between 04:00 and 14:00. In addition, battery capacities of ≥20% are now large enough to supply complete midday demand while keeping grid-drawn power below the charging input rate of the external battery. The same goes for battery capacities of ≥40% for the evening demand.

The average cumulative daily energy drawn from the grid for each taxi rank is shown in Table 3.

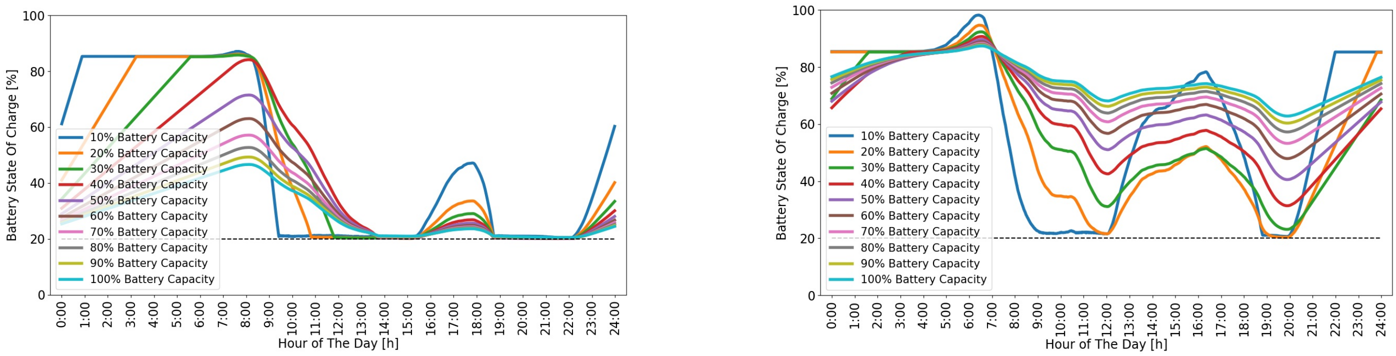
Table 3. Average daily cumulative energy drawn from the grid for each battery capacity iteration for full taxi rank area solar installation.

Battery Capacity Increment [%]	Energy [kWh] (per Taxi) Dobsonville	Roodepoort
0 [Reference]	9959 (87.4)	7680 (87.3)
10	8286 (72.7)	4043 (45.9)
20	8369 (73.4)	4058 (46.1)
30	8448 (74.1)	4101 (46.6)
40	8523 (74.8)	4134 (47.0)
50	8513 (74.7)	4142 (47.1)
60	8503 (74.6)	4138 (47.0)
70	8493 (74.5)	4135 (47.0)
80	8483 (74.4)	4133 (47.0)
90	8474 (74.3)	4130 (46.9)
100	8464 (72.2)	4128 (46.9)

As expected, the solar energy supply still does not have a significant contribution in reducing the grid-drawn energy at **Dobsonville**, where an average grid-drawn energy reduction of 15.1% across all battery capacity iteration is seen. **Roodeport**, however, has a significant decrease in grid-drawn energy, with an average reduction of 46.3%. The impact this has on reducing GHG emissions is discussed in Section 4.3.

Figure 9a confirms that all battery capacity iterations reach their minimum charge of 20% both during the midday and evening demand at **Dobsonville**. This is similar to the results obtained in Section 4.1. Even with an increased solar power supply, the recharging rate of the external battery is still insufficient. This further highlights the need for an optimal and dynamic recharging speed. This is further discussed in Section 5.

The **Roodepoort** taxi rank shows a more successful implementation of the external battery and solar PV model, as battery capacities ≥40% do not reach their minimum state of charge on average. In addition, the smaller battery capacity iterations do not obtain a full state of charge, suggesting the threshold for grid-assisted external battery charging is low enough at 85%.



(**a**) Dobsonville (**b**) Roodepoort

Figure 9. Average battery state of charge for each battery capacity iteration for full taxi rank area solar installation.

4.3. Sustainability Impact

The sustainability impact of the proposed model is assessed and quantified in terms of the GHG emissions associated with energy generation. An emissions factor of 1.06 $kgCO_2/kWh$ for grid-drawn energy is used, as determined by Pepkor for 2021 [68].

The reference grid-only charging scenario energy drawn from the grid at Dobsonville results in 10,556 $kgCO_2/day$ emitted, whereas the energy used at the Roodepoort taxi rank results in 8140 CO_2/day emitted.

For the roof area solar scenario, the average emissions across all battery capacity iterations equates to 10,978 $kgCO_2/day$ at Dobsonville and 7374 $kgCO_2/day$ at Roodepoort. As the solar energy source is classified as a zero-emissions source, the change in GHG emissions equals the change in grid-sourced energy. Thus, an emission increase of 0.4% and a decrease of 9.4% at Dobsonville and Roodepoort, respectively.

As previously mentioned, the full-area solar scenario is expected to have the biggest impact regarding sustainability. The 15.1% reduction in grid-sourced energy at Dobsonville reduces CO_2 emissions to 8962 $kgCO_2/day$, where the 46.3% reduction at Roodepoort reduces CO_2 emissions to 3959 $kgCO_2/day$.

Further advancements in sustainability are obtained by using second-life batteries from old EVs. This creates a somewhat circular life cycle within the future electric paratransit industry. However, the exact sustainability impact and the quantification thereof in terms of GHG emissions falls outside the scope of this study.

4.4. Pollution

It is important to note that the other pollutants mentioned in Section 1, such as particulate matter (PM), NO_x, and CO, are eliminated from the area where mobility takes place since the tailpipe emissions are eliminated. Pollutants may still occur at the place where electricity is generated. Similar to moving electricity to renewable generation, a proportional reduction will thereafter be achieved in the geographical proximity of the polluting electricity production. However, while GHG emissions have a global impact, regardless of where it is produced, these pollutive emissions are restricted to where they are emitted and are very much dependent on the details of the specific plant, e.g., method and efficiency of production.

5. Conclusions

For adequate sizing, adding an external battery at charging stations successfully reduces the strain on the grid resulting from the charging of a fleet of electric taxis. However, in most instances, it is found that the recharging rate of the external battery has a more critical role in reducing the eventual maximum grid load than the battery capacity itself. As the Dobsonville charging station showed, the smaller iterations of the battery capacity proved sufficient to supply the midday demand fully. But, with the afternoon demand and evening demand occurring only 3 h apart, the standard recharging threshold is insufficient to prepare the external battery charge for the latter. A hybrid charging speed solution, where the charging threshold adapts to prepare for the following peak demand optimally, is thus suggested for further work. Although an increased charging point for the few hours between peak demands will have to be drawn from the grid (given a fixed solar setup), the aim remains to reduce the eventual peak demand of 1.2 MW.

Incorporating solar PV reduces the total energy drawn from the grid and the peak grid demand. In Roodepoort, the Roof Area scenario showed that the current charging threshold is too slow for any battery capacity to support a full day's demand fully. However, with the increased solar setup, a battery capacity of merely 4400 kWh is sufficient to reduce the grid load to the minimum charging threshold of 350 kW. In addition, the more extensive solar setup also reduces grid-drawn energy for this battery capacity iteration by 58%.

From this, it can be concluded that adding an external battery and solar PV at charging stations can reduce the grid impact, but the sizing of both elements needs to be optimised. According to the successful results obtained for the Roodepoort taxi rank, an external battery capacity of 50% of the total electric taxis, coupled with a solar PV setup size of 47 m^2/taxi is sufficient to supply a full day's energy for electric taxis in this use case.

Although any reduction in GHG emissions is seen as an improvement, the results show that net-zero transport is not as simple as electrification. With sustainability being the motivation behind the call for the electrification of transport, it is clear that more effort is needed to ensure that operation does in fact reduce emissions and not only shift the source elsewhere.

Suggestions for further work include the investigation of a variable input charging threshold if a more extensive solar setup is not possible. This will require an investigation into the charging patterns of the taxis in order to prepare the external battery adequately for upcoming high-demand periods. Alternatively, a designated charging station must also be explored to serve the evening peak demand. The external battery at this charging station will have $\geq$20 h between demand times to build up charge from both a full day's solar and grid-assisted trickle charging as required. In addition, an in-depth financial model for energy-as-a-service is also required to understand if such an undertaking is financially viable.

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Abbreviations

The following abbreviations are used in this manuscript:

AC	Alternating Current
BESS	Stationary Battery Energy Storage System
CO_2	Carbon Dioxide
DC	Direct Current
EV	Electric Vehicle

FSC	Fast Charging Stations
GHG	Greenhouse Gas
GPS	Global Positioning System
ICE	Internal Combustion Engine
OEM	Original Equipment Manufacturer
RES	Renewable Energy Sources
SAM	System Advisor Model
SOC	State of Charge
V2G	Vehicle-to-Grid

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