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Grid-Sim: Simulating Electric Fleet Charging with Renewable Generation and Battery Storage

Johannes Human Giliomee [1] and Marthinus Johannes Booysen [2,*]

[1] Department of E&E Engineering, Stellenbosch University, Stellenbosch 7600, South Africa; jhgiliomee@sun.ac.za
[2] Faculty of Engineering, Stellenbosch University, Stellenbosch 7600, South Africa
* Correspondence: mjbooysen@sun.ac.za

Abstract: The inevitable electrification of the sub-Saharan African paratransit system poses substantial threats to an already crippled electricity supply network. The integration of any electric vehicle fleet in this region will require in-depth analyses and understanding of the grid impact due to charging. This allows informative decisions for sufficient planning to be made for the required network infrastructure or the implementation of applicable 'load-shifting' techniques. This paper presents Grid-Sim, a software tool that enables comprehensive analysis of the grid impact implications of electrifying vehicle fleets. Grid-Sim is applied to assess the load profiles, energy demand, load-shifting techniques, and associated emissions for two charging stations serving an electrified minibus taxi fleet of 202 vehicles in Johannesburg, South Africa. It is found that the current operation patterns result in a peak grid power draw of 12 kW/taxi, grid-drawn energy of 87.4 kWh/taxi/day, and, subsequently, 93 kg CO_2/taxi/day of emissions. However, when using the built-in option of including external batteries and a solar charging station, the average peak power draw reduces by 66%, and both grid-drawn energy and emissions reduce by 58%.

Keywords: paratransit; electric vehicle; minibus taxi; energy expenditure; grid impact; vehicle charging

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1. Introduction

The electrification of transport is on the rise in the Global North. However, the same cannot be said about sub-Saharan Africa (SSA), as this region already faces electricity supply shortcomings. The added, and mostly unknown, grid impact of charging raises great concerns when assessing the feasibility of an electrified taxi fleet. This paper proposes a software tool that uses mobility data as input to simulate the grid impact of charging a fleet of electric vehicles. Although the proposed application is in the informal paratransit industry of SSA, the tool is universal and can be used with any vehicle fleet.

1.1. Sub-Saharan Africa Paratransit

The paratransit in SSA differs from how it is known in the Global North. In this region, the term is used to describe an informal, demand-based, and organically evolved system. It operates somewhere between public and private transport and consists of multiple vehicle modes [1,2]. The most popular vehicle is the multi-passenger minibus taxi, used in South Africa, Kenya, Nigeria, Uganda, Egypt, and Ghana. In South Africa, 250,000 of these 9- to 16-seater vehicles are used by 84% (∼15,000,000 people) of road-going daily commuters [3,4].

Emissions from transports currently account for 12% of global greenhouse gas emissions, of which 4% is contributed by SSA [5,6]. An expanding middle class, population growth, and urban mitigation has caused this number to greatly increase, as the 84% increase from 2010 to 2016 has shown [7,8].

These emissions directly contribute to a reduced air quality in the region. The World Health Organization links the exposure to ambient air pollution to respiratory infections and an increasing number of lung cancer cases, amongst other health concerns [9,10]. In 2022 alone, 180,000 premature deaths were linked to bad air quality [11].

The call for the electrification of transport stems from both sustainability and increased living standard points of view. Although the net emission difference depends on the energy source with which the electric vehicle (EV) is charged, removing greenhouse gasses from urban areas is already a stride in the right direction. However, the already existing electricity supply shortcomings make the additional load of electric taxis nearly unthinkable [12]. It is thus paramount that the electrification of the paratransit industry is sufficiently planned. As there are no electric taxis operating in SSA from which grid impact estimations can be made, a simulation tool is required.

1.2. Contribution

In this paper, we propose a novel simulation tool to simulate the grid impact of an electric vehicle fleet. The software, written in Python, uses simple vehicle (mobility + specifications) and charging station (location + specifications) information as input and produces simulated electric vehicle energy usage and grid load profiles as output. This tool is called 'Grid-Sim' and is publicly available [13]. The application for this contribution is to allow stakeholders to make informed decisions regarding electrical upgrades for electrifying a vehicle fleet.

A limitation of our contribution is that user input that is representative of an EV, both for mobility data and charging infrastructure, is required.

Although not the focus of the contribution of this paper, a Grid-Sim extension for the addition of external stationary batteries and solar charging stations is also assessed for grid impact reduction [14].

2. Literature Review

To understand why quantifying the grid impact of the charging of an EV fleet is important, in this section we look at the current electricity supply situation in the region. In addition, we also assess the background of existing grid impact simulation software and similar tools.

2.1. Electricity Supply Quandary

For the majority of the SSA population, access to a stable electricity supply is far-fetched [15–17]. This includes an inadequate electricity supply network, immediate power delivery (power), and energy delivery over time. Even in the more developed countries in SSA, electricity supply shortages are a part of everyday life.

Furthermore, it is shown that electricity consumption is positively correlated with economic growth. Introducing an additional, unknown load on the power grid will likely exacerbate the decline in the quality of the electricity supply, thereby hindering economic growth [18].

As such, the three characteristics that needs to be considered when analysing the electrification of transport includes the economic, renewable energy, and infrastructure perspectives, as described by Mopidevi et al. [19]. This paper focuses on the renewable energy and infrastructure perspectives. Within infrastructure perspectives, various aspects needs to be considered. These include different charging configurations, renewable energy integration for off-grid purposes, optimisation techniques, and various energy management approaches [20,21].

In South Africa, which is ranked 3rd in the United Nations human development index in SSA, rolling blackouts have been a common occurrence since 2008 [22,23]. Locally known as 'load shedding', rolling blackouts occur on a partially scheduled basis. Eskom, the sole national electricity distributor, defines load shedding as a planned switching off of electricity to lower the demand on the grid. These blackouts last for two to four hours and occur one to four times a day, depending on the stage of load shedding, where the stage number represents the GW capacity shed. Although the application of load shedding is not new, in 2022 load shedding reached a new height with 3773 h of load shedding, an increase of 322% from 2021 [24]. Although South Africa has an installed capacity of 48,186 MW, only 58% was readily available in 2022 [25].

Considering the 250,000 taxis in South Africa, even electrifying a small percentage of the fleet will result in a significant grid load increase [26]. As Abraham et al. [27] have shown, the majority of these taxis operate in a somewhat synchronised manner. Thus, the charging opportunities are also in unison. Assuming a Level 2 charging speed (up to 22 kW), electrifying a mere 15% of taxis could result in an added 1 GW grid load [28].

On a national scale, Qian et al. [29] determined that a 10% EV penetration in the United Kingdom will result in a 17.9% increase in peak daily demand for an uncontrolled charging scenario.

Understanding the exact load profile of electric taxi charging will therefore assist in the sufficient preparation. Through this, the required capacity can either be accounted for in future grid upgrades within the operational area of a taxi or assist with a 'load shifting' approach. This approach aims to reduce the impact on the grid by limiting concurrent charging at a given time and thus damper new peak loads [26].

Various charging strategies are included under this umbrella term, such as vehicle-to-grid implementations [30–32], renewable energy source integration [33], stationary battery storage systems [14,32,34], and smart charging strategies [32,35].

However, to implement these strategies, the load profiles of electric taxi charging is required. In the absence of such recorded data, mathematical models or simulation tools are required to estimate this impact.

2.2. Existing Grid Impact Simulation Software

Currently, various strategies exist for determining the grid impact of charging an electric vehicle, with varying input data requirements. Although many of the studies conducted on this delve into reducing the impact with load-shifting strategies, the contribution of this paper only focuses on determining the base load impact of charging.

In light of unavailable comprehensive travel behaviour data, Li et al. [36] developed a statistical transportation model that utilises survey data, which estimates EVs' temporal availability in China. They implement kernel density estimates to determine the probability density function of EV availability at each hour for each type of day (weekday or weekend). This is then used to identify when the vehicle would be charging.

However, in the context of this study, grid impact tools using vehicle mobility data as input allow for a more direct comparison to our contribution.

One such study was conducted by Quirós-Tortós et al. [37], who, in contrast, warns against the use of survey data as input as they can produce unrealistic demand profiles. They employed probability density functions that relied on Gaussian mixture models to describe the mobility patterns of electric vehicles. Another study, conducted by Schäuble et al. [38], used mobility data from an electric vehicle to simulate its charging load profile. As previously mentioned, such data are not available in the paratransit industry of SSA. Mobility data from current operational internal combustion engine (ICE) taxis need to be used if mobility data are required as input to a grid impact simulation tool.

To our best knowledge, there is no publicly available simulation tool that simply uses vehicle mobility data to produce a load profile. The purpose of this paper is to fill the gap in the literature.

3. Method

This section provides an in-depth analysis of the data handling and calculation process of Grid-Sim. The process is broken down into three chronological steps, as presented to the user in the start menu: *Initialise Scenario*, *Check and Prepare Files*, and *Run Grid-Sim*. Each step is discussed in detail to provide a comprehensive understanding of the Grid-Sim process.

An extension of Grid-Sim, where external batteries and a solar charging station is integrated to reduce the grid impact, is shown in [14]. The methodology of this extension is already covered in depth in that paper and will not be repeated here. However, the recommended battery and solar sizing by Giliomee et al. [14] is implemented for comparison to grid-only charging.

An overview of the inputs required and the outputs generated by the base model of Grid-Sim is shown in the flowchart in Figure 1.

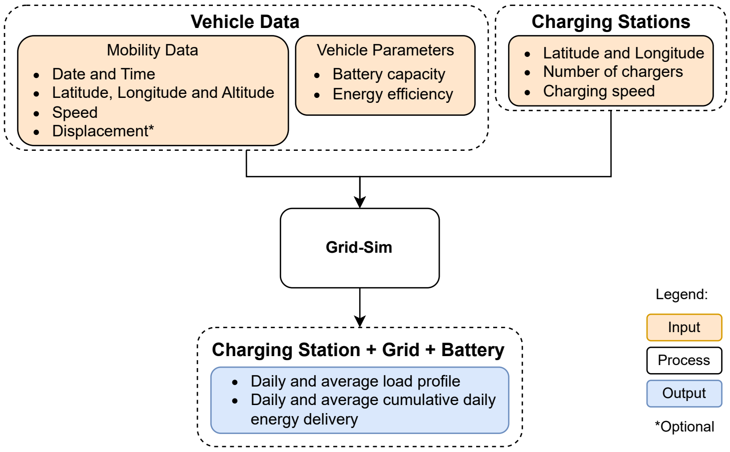


Figure 1. An overview of the inputs and outputs associated with base Grid-Sim.

When running Grid-Sim, the user is asked for a path to a folder in which they want the simulation to take place. A validation check for a valid directory is immediately performed. If the given directory is valid, the user will be presented with the main menu, consisting of the three aforementioned steps.

3.1. Scenario Initialisation

Option 0: The Initialise Scenario in Grid-Sim presents several prompts to the users for scenario initialisation. If the folder path given by the user is not empty, they will be instructed to empty it before the scenario initialisation process begins.

During scenario initialisation, the user is prompted to input information about the vehicle fleet and charging stations, where the number of vehicles and number of charging stations are required, respectively. However, this can still be modified at a later stage.

Further parameters for the vehicle fleet, such as names, battery capacity, and energy efficiency can either be entered though the user interface or directly in the *Vehicle_Parameters.csv*file at a later stage. Similarly, parameters for each charging station, such as names, location, charging speed (power), and charging outlets can also either be entered when prompted or later in the *Charging_Station_1.csv* file.

As assistance to the user, various preset vehicles are made available. Each preset vehicle class, along with its parameters, is shown in Table 1. These parameters are only suggestions and are fully modifiable to the user if they wish to use other EVs as a reference. If the user only wishes to modify the battery capacity, it is suggested that the energy efficiency is modified according to the suggested ratios by Abraham et al. [39].

Table 1. Preset vehicle classes in Grid-Sim.

Vehicle Class	Battery Capacity (kWh)	Energy Efficiency (kWh/km)	Ref.
Saloon	60	0.15	Tesla Model 3 [40,41]
SUV	60	0.18	Hyundai IONIQ 5 [42]
Minibus	60	0.55	Higer H5C EV [39,43]
Bus	125	0.83	Tata Ultra 9/9 m AC Electric [44]

In the extended version of Grid-Sim, users have the option to include external batteries and a solar charging station. Here, the battery capacity and charging speed parameters are required. In addition, an energy profile output from the System Advisor Model (SAM) is also required for solar power generation.

Once the preliminary inputs are provided, the user is tasked to further populate the *Input* folder, as shown in the GitHub README document. The structure of the required input files is shown in Figure 2.

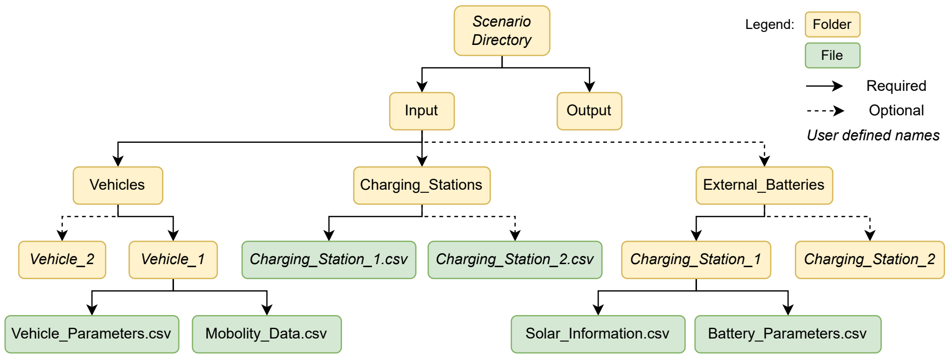


Figure 2. The input folders and files that are required and checked for in step 1.

Thereafter, the user can proceed to step 1 by pressing *ENTER* or by restarting Grid-Sim and selecting option 1 from the start menu.

3.2. Data Preparation

The second step in running Grid-Sim is option 1: Check and Prepare Files. This step entails a comprehensive examination of all input files to ensure the availability of all required files in their designated locations. Subsequently, the data undergo processing to prepare them for the subsequent simulation phase.

At this point, all input files should be provided in the prescribed format and location, as stated in the *README* file and input directory branch in Figure 2. Grid-Sim will verify that the necessary files are provided and inform the user of any shortcomings. Once all the checks are successfully completed, the user is informed through a printed message and data preparation automatically commences.

Grid-Sim is configured to analyse the load profile on a per-minute level. Thus, the objective of data preparation is to generate a mobility data sample for each minute of an active day. During data preparation, the output of each individual step is written and saved in a dedicated comma-separated values (CSV) file.

The data preparation steps are summarised as follows:

1. Downsample mobility data;
2. Segregate mobility data by day;
3. Interpolate the data;
4. Extrapolate the mobility data for a full day.

The data preparation process begins with the downsampling of the data to obtain a single sample per minute. This involves extracting the initial input data sample for each minute while discarding the remaining input data for that particular minute. However, if input data for *Displacement* is given, it will be summed and incorporated into the extracted data sample. Additionally, a speed filter is applied during this step to address GPS noise. In this paper, we have selected the *GPS_speed_noise_threshold* variable as 2 m/s.

Thereafter, the mobility data are segregated by day to facilitate grid impact analysis on a daily basis. To achieve this, a distinct folder is generated for each day in which mobility data are found in the mobility input files. Within these folders, the mobility data for each vehicle are further segregated and stored separately based on the corresponding days for which mobility data are provided for that particular vehicle

Following that, the data will be interpolated. During this step, Grid-Sim generates virtual data samples for each minute that is absent in the original input mobility data. It is important to note that this step solely aims to bridge the gaps between the first and last input sample for each day (interpolate) and does not extrapolate the data for the entire day. For minutes that are found to be missing in the input file, virtual data points are created based on the preceding available sample. The *Latitude*, *Longitude*, and *Altitude* data remain constant until the next input sample is given. The *Speed* and *Displacement* are both set to 0 for the virtual data points, with the time incremented by a single minute for each data sample.

The final stage of the data preparation process involves the extrapolation of the data to cover the entire day, resulting in a total of 1440 mobility data samples. This extrapolation is accomplished by utilising the information from the first and last input data samples to generate virtual data samples. The first available data sample is used to create virtual data samples from minute 0 until the time of the first data sample, while the last data sample is used to generate virtual data samples up to minute 1339. During this extrapolation, the *Latitude*, *Longitude*, and *Altitude* information again remain constant for the virtual data points, while the *Speed* and *Displacement* are set to 0.

This concludes the mobility data preparation step of Grid-Sim. At this stage, the mobility data of the vehicles cannot be altered. However, it is still possible to modify the vehicle parameters and charging station information. This flexibility enables users to conduct multiple simulations using the same mobility data while making adjustments to specific vehicle and charging parameters each time, without the need to repeat the entire data preparation process.

In the extended version of Grid-Sim, the solar charging station information is treated similarly to the mobility data. It is separated into daily folders for active days within the scenario and extrapolated to provide minute data samples.

3.3. Simulation

Once the data preparation process is finalised and the input parameters are configured, the next step involves selecting option 2: Run Grid-Sim. The simulation process in Grid-Sim follows a similar approach to the data preparation, where the outcome of each simulation step is made accessible to the user for analysis purposes.

The simulation steps are summarised as follows:

1. Power offtake calculated;
2. Determine battery level and charging status;
3. Determine grid impact;
    (a) External battery load shifting.

The simulation process commences by evaluating the power offtake of the vehicle for each data sample. This is calculated using the given kWh/km vehicle input parameter. If the mobility data input includes *Displacement* information, it is directly utilised to calculate the energy consumption for each data sample accordingly. In the absence of *Displacement* data, the GPS information is used to estimate the straight-line distance between input samples. To accomplish this, the Haversine formula, available in the geopy Python library [45], is utilised. The calculation follows an approach where the displacement is determined by calculating the distance from the current data sample to the previous data sample ($n - 1$), considering both the *Latitude* and *Longitude* information. Additionally, the change in *Altitude* is taken into consideration. Subsequently, the energy consumed from the previous data sample to the current data sample is calculated.

The second step in the simulation process is were the battery level and charging status are determined. In this phase, the power offtake output file of each vehicle is simultaneously analysed on a per-minute basis. At this point, a battery depletion check is conducted at the end of each data sample iteration. If the battery charge falls below the chosen threshold, the simulation is halted precisely at that data point for all vehicles, and subsequent simulation steps are only executed up to this point. For each vehicle, its location is assessed to determine if it is stationary at a charging station. The procedure for conducting this check, as well as the subsequent verifications for successful vehicle charging, is outlined in Algorithm 1.

Algorithm 1: An overview of how Grid-Sim determines if vehicle charging is initialised

```
def charging_curve(i): return (1 − math.exp(((i ∗ 100) − 85)/4)/120)
if vehicle.battery != 100 % then
    if vehicle.speed == 0 then
        for charging_station in Charging_Stations do
            if vehicle.location == charging_station.location ± charging_station_radius
             then
                if charging_station.available_chargers ≥ 1 then
                    if vehicle.stationary_time_at_charger ≥ stationary_threshold then
                        vehicle_is_charging(vehicle.name, charging_station.name)
                        reduce_available_chargers(charging_station.name)
                        charging_speed =
                         get_charging_speed(charging_station.name)
                        power_delivered = charging_speed*charging_efficiency
                        if vehicle.state_of_charge ≥ 0.85 then
                            power_delivered =
                             power_delivered*charging_curve(vehicle.battery)
                        end
                        increase_vehicle_battery_level(vehicle.name,power_delivered)
                        break
                    end
                end
            end
        end
    end
end
```

Table 2 presents the modifiable variables that have an impact on the simulation and their respective values chosen for this study. The chosen values are based on the input dataset, as further described in Section 4.

Table 2. Variables that are modifiable to the user.

Variable	Value	Description
weekend_results_only	True	Deletes weekend results for weekday-only analysis
delete_folders	False	Deletes intermediate folders once used
GPS_speed_noise_threshold	2 m/s	Filter for GPS noise at low speed; zeros out speed
stationary_time_threshold	1 min	Stationary time required at charging station before charging
unusable_capacity	20%	Minimum SOC of vehicle battery
charging_station_radius	10 m	Defines the total area of the charging station from the defined location
charging_efficiency	1	Power delivery efficiency from grid to vehicle
external_battery_grid_charging_threshold	85%	Maximum SOC to which the grid will charge the external battery
external_battery_discharging_threshold	20%	Minimum SOC of external battery

The check for a depleted battery is performed after each sample where a vehicle has a reduced SOC. When a depleted battery is detected based on the chosen usable capacity threshold, the message shown in Figure 3 is printed. The subsequent course of action is left to the discretion of the user.

The grid impact analysis is performed based on the output file generated in the preceding step. The aforementioned CSV file stores the name of the charging station when a vehicle is charging. After reading all vehicle files, the total grid impact is determined by analysing the difference in the state of charge (SOC) of the vehicles at each minute. Power and energy profiles are then generated for each charging station for each active day, along with an average profile for the entire simulation period.

```
The simulation could not be completed. It was stopped on 2019-01-01 at 07:20:00
as Vehicle Vehicle_1's battery breached the miminum state of charge of 15 state
at (-26.161135,27.8698512).
Either increase battery size, or ensure charging prior to this timestamp.
```

Figure 3. The displayed message for an unsuccessful simulation.

If external batteries are included in the scenario, the grid impact is now re-calculated. In this case, the previous grid impact results can be considered the charging station to vehicle power delivery, where results from this step yield grid to charging station results. Outputs from this step include the grid impact and external battery SOC for each charging station for each day of the simulation, as well as an average profile for the simulation period.

3.4. Assumptions and Limitations

One limitation of Grid-Sim is that it requires mobility data from a fleet of electric vehicles or data that are representative of an EV's capabilities as input. Given the different fuel/charge times and ranges of ICE vehicles and EVs, the user should take care when using tracking data acquired from ICE vehicles.

Furthermore, the user must provide sufficient input regarding the charging infrastructure. This includes details such as the number of charging stations, their locations, the number of outlets, and the charging speed. Insufficient charging infrastructure input, leading to scenarios where vehicles deplete their battery charge, will result in incomplete simulations, as previously mentioned.

4. Input Data

In the absence of available mobility data that are representative of an EV in SSA, an operational plan designed for electric taxis in Johannesburg, South Africa, is used as input data in this paper. This dataset, containing origin and destination data of 202 taxis, was developed by the World Bank [46]. As part of the dataset, two taxi ranks are identified as charging stations, namely Dobsonville (serving 114 taxis) and Roodepoort (serving 88 taxis). These stations, along with the routes the taxis serve, are shown in Figure 4.

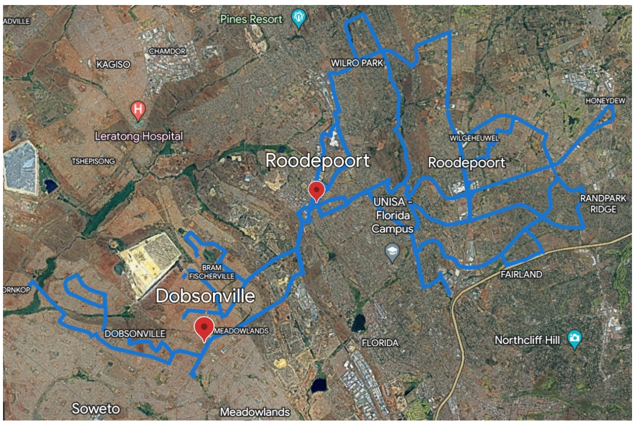


Figure 4. Taxi ranks (charging stations) along with the routes they serve in Johannesburg, South Africa as shown by Google Earth [46,47].

As required for Grid-Sim input, a mobility dataset was created out of the operational plan. This entails separating the journey into two separate data points, replacing the location names with GPS traces, and adding speed information. As each data sample gives a stationary location, all speed information is set to zero.

In this paper, only the weekday grid impact is analysed. Thus, no weekend mobility is taken into account and it is removed from the operational plan. As each weekday's operation is identical, the same grid impact will be seen over a year's operation for a grid-only charge scenario.

For analysis of the addition of a solar charging station and external battery, the mobility data are extrapolated over a month for each season according to irradiance information: January (best), May (worst), August (intermediate), and November (intermediate).

Input Parameterisation

As the parameterisation of both the vehicle and charging station parameters are dependent on the chosen input mobility data, parameters according to a World Bank study are used [46]. The parameterisation for both the external batteries and solar charging stations is conducted according to the recommended ratio per taxi by Giliomee et al. [14].

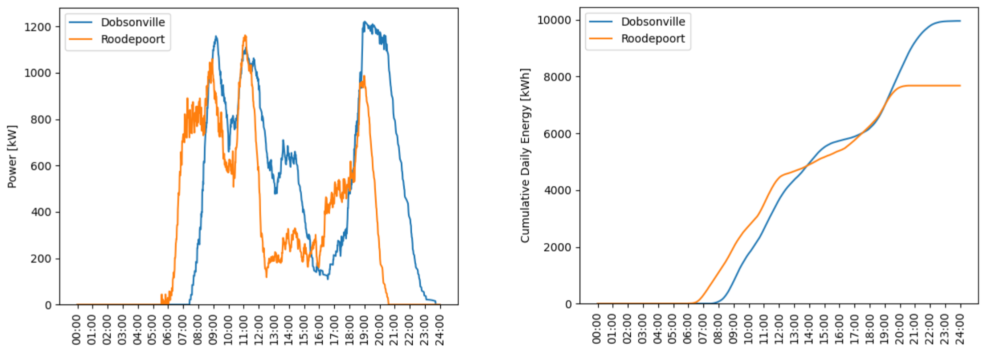
All input parameters are summarised in Table 3.

Table 3. Input parameters for all input entities.

Parameter		Value
Vehicle	Battery capacity	100 kWh
	Energy efficiency	0.55 kWh/km
Charging station	Charging speed (power)	22 kW
	Charging outlets (per station)	56
External battery	Capacity	50 kWh/taxi
	Charging input	4 kW/taxi
Solar plant	Rated (peak) power	9.45 kW_{pk}/taxi

5. Results

To facilitate scalability for evaluating different taxi fleets, the results are presented in two ways: on a per-taxi (per-vehicle) basis and on a per-charging-station basis. The power and energy delivery profiles for each charging station are shown in Figure 5.



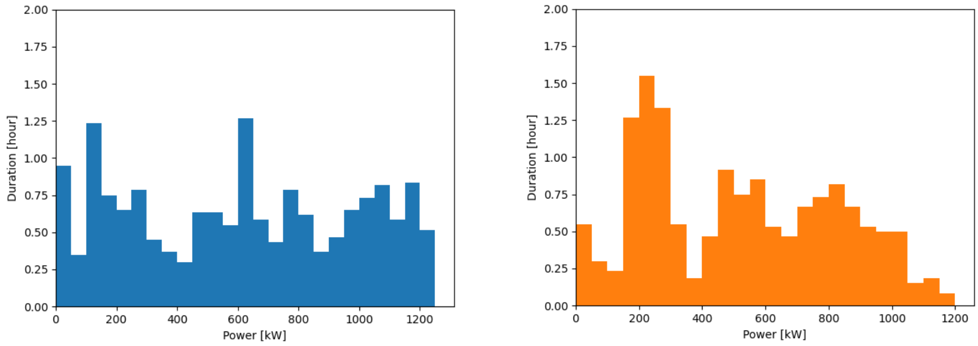
(**a**) Power profile (**b**) Energy profile

Figure 5. Grid impact for a weekday's operation for grid-only charging.

The total daily energy demand, as depicted in Figure 5b, is observed to be 9959 kWh (87.4 kWh/taxi) for Dobsonville and 7680 kWh (87.3 kWh/taxi) for Roodepoort. This near exact divide between the two charging stations demonstrates the accuracy of the operational plan used as input. Considering an emission factor of 1.06 kg CO_2/kWh [48], the total daily emissions are estimated to be 18,697 kg CO_2 (93 kg CO_2/taxi).

Using the energy profile, viable alternative and renewable sources can be identified accordingly. In this study, one potential source investigated is solar power. However, upon examining the energy profiles, it becomes evident that the energy demand is concentrated in the early morning hours and the late afternoon or evening. Consequently, the optimal midday power delivery of a solar plant does not align with the charging requirements of this vehicle fleet. While numerous energy storage options are available, this study focuses on evaluating a simple external battery. Further assessment of this approach is presented in Section 5.1.

However, although the assessment of the sustainability of the electrification of transport is based on the energy source and usage, the peak power delivery of the load profile is also a concern in the region. As depicted in Figure 5a, the peak power demand at Dobsonville is 1221 kW (10.7 kW/taxi), and it is 1162 kW (13.2 kW/taxi) at Roodepoort. To visualise the duration for which a cluster of power is required, we aggregate the power draw over each simulation minute. This is presented as histograms in Figure 6.



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

Figure 6. The time for which a cluster of 50 kW is drawn from the grid.

As shown, the high power demand lasts for quite a number of hours each day. The timing of these peak hours predominantly falls in the early morning and evening, as illustrated in Figure 5a. The strong correlation between the peak demand for taxis and the peak national demand raises concerns and emphasises the need to explore load-shifting strategies. The investigation of load-shifting techniques is discussed in detail in Section 5.1.

To provide a broader perspective on the peak grid load demand per taxi, it is essential to consider the estimated total number of taxis in operation across South Africa. Assuming an average peak grid load of 12 kW/taxi, electrifying a fleet of 250,000 taxis would require an additional generation capacity of up to 3 GW. However, it is crucial to note that the currently available installed grid capacity is only 52% (26,612 MW) as of May 2023 [25]. Thus, electrifying the South African taxi industry would necessitate a 11.3% increase in readily available generation capacity. Note that these calculations are based on the optimised input dataset used in this study, specifically designed for electric transport. If the current operation is maintained, the peak demand would be considerably higher.

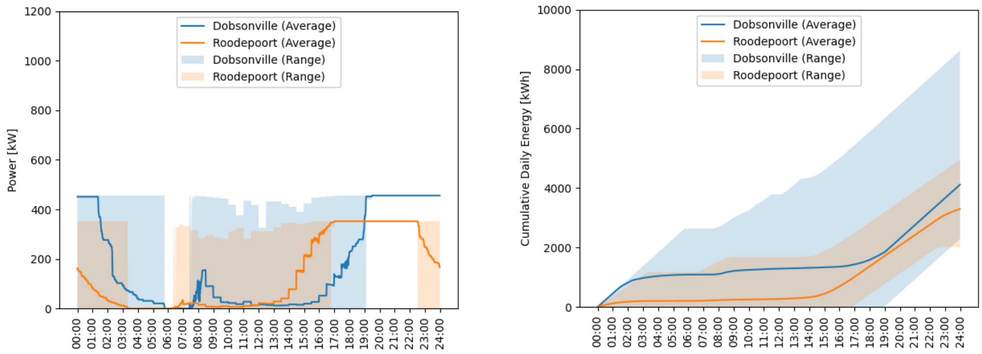
5.1. Reducing Grid Impact

The load-shifting technique implemented in Grid-Sim involves the integration of an external battery, which can be charged from both a solar charging station and the grid as required. The specifications of these auxiliary systems are shown in Table 4.

Table 4. Sizing of the external batteries and solar charging stations.

Parameter		**Charging Station** Dobsonville	Roodepoort
External battery	Capacity	5700 kWh	4400 kWh
	Charging input	456 kW	352 kW
Solar plant	Rated power	1077 kW_{pk}	832 kW_{pk}

The updated average power and energy delivery profiles from the grid for each charging station are shown in Figure 7. This section provides analysis of the average values obtained for each result. Although the vehicle power and energy demand remain constant for each day in the simulation period, the variation in solar irradiance invokes the need to analyse the average profiles.



(**a**) Power profile (**b**) Energy profile

Figure 7. Grid impact for a weekday's operation with the inclusion of an external battery and solar charging station.

The average total daily energy drawn from the grid, as depicted in Figure 7b, amounts to 4115 kWh (36.1 kWh/taxi) for Dobsonville and 3300 kWh (37.5 kWh/taxi) for Roodepoort. However, the high upper range seen at Dobsonville indicates that irregularities of solar power generation have a significant effect on daily grid energy requirements. With the same aforementioned emission factor, this equates to total daily emissions of 7860 kg CO_2 (39 kg CO_2/taxi) from grid-drawn energy. Since the energy obtained from the solar charging station is regarded as fully sustainable, the implementation of the load-shifting technique has successfully reduced both grid-drawn energy and CO_2 emissions by 58%. This highlights the significant environmental benefits of integrating renewable energy sources into the charging infrastructure.

It is found that both charging stations' maximum average power draw does not exceed the external battery charging input speed of 4 kW/taxi. Thus, the maximum average power draw is observed to be 465 kW for Dobsonville and 352 kW for Roodepoort. This translates to a reduction from grid-only charging of 63% at Dobsonville and 71% at Roodepoort.

These findings indicate that the load-shifting system has been accurately sized to reduce the peak power demand. In addition, the peak power is shifted to be drawn over nighttime. Although this still slightly overlaps with the national evening demand, further optimisation in the timing of this power draw can result in a load profile that does not clash with the national demand.

To gain a comprehensive understanding of the battery's performance and utilisation throughout the simulation period, we examine the average state of charge of the external battery, as depicted in Figure 8.

Figure 8 shows that at no point over the battery SOC range does it deplete to the minimum SOC of 20%, and it rarely fully charges at later stages of the day. This suggests successful sizing of the external battery capacity as the vehicle solely charges from the battery.

As it is now clear that the external battery never depletes to the lower threshold, which would not allow vehicle charging, we revisit the power profiles shown in Figure 7a. Since the vehicles does not require charging from the grid in this scenario, it is clear that the irregularities in grid-drawn power from 06:00–11:00 are due to the power delved by the solar plant not meeting the minimum charging threshold. Hence, the grid has to assist to charge the external batteries at the minimum threshold. Smart charging strategies or a larger solar plant would prevent this from happening and ensure limited power is drawn from the grid during the day, and, subsequently, that grid-drawn power is only required during nighttime.

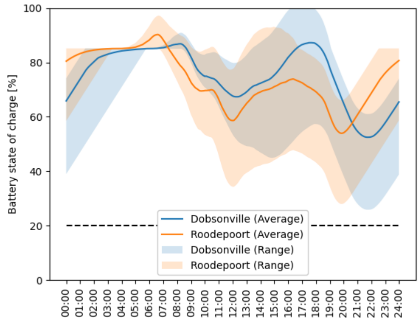
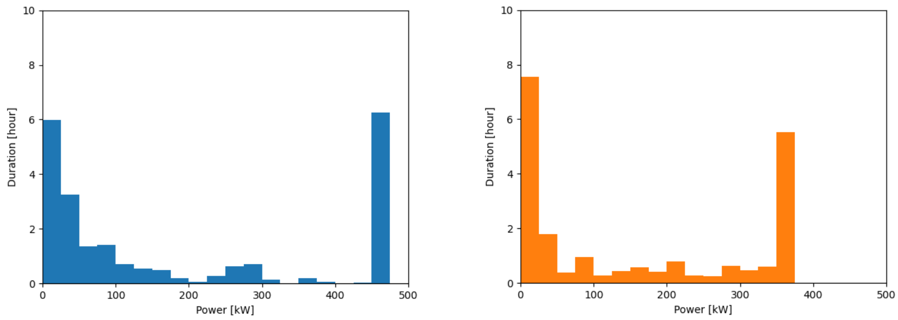


Figure 8. Average and range of external battery state of charge over the entire simulation period. As the external batteries start the simulation with a 100% SOC, the first day's results are removed from the range plot for a more realistic representation for SOC range over the simulation period.

To complete the analysis of the load profile for the load-shifting scenario, we again look at the time for which a cluster of grid-drawn power is required. This is illustrated in the histograms in Figure 9.



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

Figure 9. The time for which a cluster of 10 KW is drawn from the grid in the load-shifting scenario.

Furthermore, the implementation of the load-shifting system not only reduces the average peak grid load but leads to a more stable average grid power draw. This enhanced stability enables stakeholders to plan and design power delivery profiles more precisely, for which the exploration of alternative energy sources that can be sized based on the specific time duration for which a particular power level needs to be supplied.

6. Conclusions

This paper introduces Grid-Sim, a software tool designed for analysing the grid impact implications of transitioning a vehicle fleet to electric power. The tool is applied to evaluate load profiles, energy demand, load-shifting techniques, and emissions for two charging stations located at taxi ranks in Johannesburg, South Africa.

The outputs generated by Grid-Sim shed light on the challenges associated with the electrification of taxi fleets, particularly in regions facing electricity shortages. The analysis reveals the timing of peak power demand and the magnitude of daily energy requirements, both of which present significant hurdles. However, this understanding of demand profiles provides valuable insights for stakeholders, enabling them to plan necessary infrastructure upgrades and consider the implementation of load-shifting techniques as part of their vehicle fleet electrification strategies. Furthermore, the load-shifting capability offered by Grid-Sim demonstrates how power demand can be effectively shifted, energy requirements can be reduced, and overall sustainability can be improved in the process of electrifying a vehicle fleet.

The findings of this study clearly indicate that the nationwide electrification of the minibus taxi industry is currently unfeasible given the existing electricity supply conditions, assuming no changes in operations. The projected additional load of 3 GW would exert a substantial strain on the region's power resources, where each gigawatt of available electricity directly affects public access to power. Considering the increased load demand as a reduction in electricity availability, the implementation of an electric minibus taxi industry will lead to an additional 4 to 5 h of daily power cuts for the general public (two-stage increase in load shedding).

The load-shifting technique incorporated into Grid-Sim, implemented through the use of external batteries and solar charging stations, gives an indication of how alternative energy sources can reduce both the grid impact and CO_2 emissions. With the selected sizing parameters, the findings reveal a remarkable reduction in average peak power draw of 66% and a substantial decrease in grid-drawn energy of 58% for both charging stations. Moreover, the improved stability in the grid power draw offers valuable insights for optimising the allocation and utilisation of energy resources.

In conclusion, Grid-Sim emerges as a valuable tool that offers stakeholders valuable insights into grid planning, resource allocation, and the integration of renewable energy sources to enhance sustainability and minimise grid impact. Although applied to the specific case of the South African minibus taxi industry in this paper, its utility extends to any vehicle fleet operator, such as logistic companies. By utilising Grid-Sim, a comprehensive understanding of the grid impact of electrified vehicle fleets is achieved, providing valuable insights for sustainable transportation planning and emissions reduction strategies.

Future enhancements to Grid-Sim can involve the integration of a dynamic power-offtake software tool that considers the vehicle's mobility data to calculate energy depletion more accurately. This would provide a more realistic representation of the vehicles' energy consumption patterns. Additionally, the load-shifting technique can be further investigated by exploring advanced energy storage technologies and optimising charging strategies. This would enable a more efficient utilisation of renewable energy sources and further enhance the sustainability of electrified transport systems.

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Abbreviations

The following abbreviations are used in this manuscript:

CO_2	Carbon Dioxide
CSV	Comma-Separated Values
EV	Electric Vehicle
GPS	Global Positioning System
ICE	Internal Combustion Engine
SAM	System Advisor Model
SOC	State Of Charge
SSA	Sub-Saharan Africa
SUV	Sport Utility Vehicle

The following symbols are used to represent the corresponding parameters:

n	Data sample

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