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Three shades of green: Perspectives on at-work charging of electric vehicles using photovoltaic carports

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Abstract

Electric vehicles (EVs) are widely heralded as the silver bullet for greening personal transport. However their eventual impact in South Africa, a developing country with a low-capacity carbon-heavy grid, is questionable. This paper examines the potential impact of electrification of the vehicle fleet in South Africa, and explores the concept that large employers (or car park owners) could take advantage of the country's abundant sunshine and provide photovoltaic (PV) solar carports for employees (or parking clients) to charge their vehicles while at work. We assess the extent to which this would reduce the potential burden on the national grid, and also consider the economic perspectives of the vehicle owners and the service providers. Our assessment employs a mobility model and a battery model for the vehicles, and solar simulation with measured data for the PV generation. We show that without the provision of additional solar generation, charging four million vehicles from the grid would exceed the grid's capacity. Further, the carbon footprint of an electric vehicle charged from the grid would be greater than that of a petrol-fuelled vehicle, negating any potential benefits of electrification. However, we demonstrate that photovoltaic charging at work renders electric vehicles more carbon-friendly than petrol equivalents, and has substantial financial benefits for the vehicle owner, the service provider, and the grid.

Keywords: Electric vehicle; Photovoltaic solar charging; Photovoltaic solar carport;

1. Introduction

South Africa, ranked the world's fourteenth largest CO_2 emitter in 2015, is hamstrung by its struggling coal-dependent national electricity utility, which frequently applies rolling blackouts during peak times to prevent a national shutdown (Ghosh, 2019; McSweeney and Timperley, 2018; Styan, 2015). Coal accounts for more than 75% of the country's energy supply, with an annual CO_2 footprint of 512 billion kg (DoE 2019a, DEA 2018). Added to this, the South African road transport sector is responsible for 43 million kg of carbon emissions from combustion engines per year (Tongwane et al., 2015).

A move to electric vehicles has been internationally advocated to reduce combustion emissions. The exact number of these vehicles imported into South Africa was not publicly available at the time of writing but it was estimated to be less than 1000 (Mavuso 2019, Malinga 2019, Hussain 2019). While the current penetration rate is low, it is just a matter of time before these vehicles appear in much greater numbers in South Africa. Knobloch et al. (2020) when investigating emission reductions from use of electric vehicles across 59 world regions, including South Africa, found that the full life-cycle emissions from average electric vehicles could be higher than those of new efficient petrol vehicles. Therefore, even though electric vehicles are generally seen as one way to reduce emissions; given the coal dependence of the national utility, Eskom, their widespread adoption could perversely increase emissions. Moreover, charging patterns could increase the likelihood of rolling blackouts during peak times (Niselow, 2019).

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Fortunately, South Africa has high levels of insolation (a measure of solar energy at a particular place over a specified time). Most areas average more than 2500 hours of sunshine per year and have average solar-radiation levels between 4.5 and 6.5 kWh/m_2 per day (DoE, 2019b). However, electric vehicles tend to be charged at home at night. One way to make the best use of solar energy, without the need for expensive battery storage, is to charge vehicles during the day, using a solar photovoltaic carport at the workplace. In South Africa, with its limited public transport, approximately a third of South Africa's estimated 10 million households use a vehicle to drive to work each day, but the vehicle spends most of the day unused (De Villiers, 2019).

This paper describes a study which explored the impact of electric vehicle charging for home and workplace scenarios in South Africa, a country with a coal-driven and constrained national grid. The results demonstrate how the timing of charging can optimize solar energy usage and reduce demand on the grid, demonstrating the real advantages of work-place charging for electric vehicles.

2. Background

Given the growing prominence of electric vehicles, researchers have begun to ask questions about their use and impact. They have investigated such areas as battery technologies, charging strategies, and impact on supply networks and generation utilities. We review nine studies we identified: Li et al. (2016), Monigatti et al. (2012), Qian et al. (2011), Leemput et al. (2014), Chandra Mouli et al. (2016), Babrowski et al. (2014), Quiros-Tortos et al. (2018), Kara et al. (2015) and Harris and Webber (2014). Our study builds on three specific areas of this electric vehicle research: the effect on the grid of increasing electric vehicle penetration; load-shifting applied to electric vehicle charging; and mobility and usage models used in electric vehicle studies.

2.1. Grid effect

In a study of the impact of electric vehicles and different charging strategies on the grid in China, Li et al. (2016) assessed the aggregated load and the economic and environmental impacts. They compared uncontrolled charging with centralized control charging strategies. In one strategy, they considered electric vehicles not only as a load but also as a grid-stabilizing energy source in a vehicle-to-grid (V2G) configuration. In this model, vehicles were charged either at home or whenever they were parked. The study took 2030 as the baseline year, which determined the number of vehicles considered, the available infrastructure, and the expected generation capacity from either renewable or non-renewable sources. Estimating the generation changes required to meet the demand, they found a 3 to 4% increase in coal consumption would be needed, and concluded that even that small increase could put grid stability at risk. However, the stability would depend on the charging strategy used. Controlled charging strategies, such as V2G, could help prevent additional peak loads and reduce the risk. However, because the quality of China's coal varies, in some regions these strategies would produce higher CO_2 emissions than traditional internal combustion engine vehicles. In New Zealand, Monigatti et al. (2012) ran a simulation similar to that used by Li et al., but incorporating wind generation as the energy source and looking particularly at how V2G strategies could help to increase New Zealand's use of wind generation. Using electric vehicles to balance the required generation and the load, they found that peak generation requirements could be substantially decreased by using a million electric vehicles in V2G operations.

Qian et al. (2011) devised a method to model the load from electric vehicles charging in a distribution network. To test this method, they simulated a typical distribution system in the UK and examined the loads, split between residential, industrial and commercial areas. They considered domestic charging, public charging and smart charging. The smart charging scenario optimized the number of vehicles charging at a given time to reduce costs and prevent new peak loads. This was designed as a future scenario and assumed a wide incorporation of communication and metered charging technologies. While this is a simpler way to reduce the grid impact than the controlled charging discussed by Li et al. (2016), it would be hard to implement in a developing country like South Africa that is already financially constrained and struggling to keep up with technological advances. Qian et al.'s study found that a 10% penetration of electric vehicles would increase the daily peak demand by 17.9% for uncontrolled domestic charging. This scenario was found to have the highest peak demands, while their smart charging proved to be the most beneficial. However, they found that while smart charging can prevent an increase in legacy peaks, it can cause new peak loads from chargers starting simultaneously.

In a Belgian study, Leemput et al. (2014) evaluated the impact of vehicle charging strategies on the power profile, voltage magnitude and voltage imbalance of a residential grid. The two strategies they investigated were uncoordinated charging and ”peak shaving”, both with and without voltage droop. They simulated a residential grid of 39 households, each with an electric vehicle, using Flemish electricity usage profiles for these households, with the addition of some residential photovoltaic energy generation. While the model also allowed vehicles to be charged at a workplace, that energy usage was not included, since the workplace was not within the residential grid. They found that the simulated grid failed to comply with European voltage standards when uncoordinated charging strategies were used. This was resolved when peak shaving techniques were applied.

2.2. Load shifting

Load shifting, a common theme in electric vehicle research, is a logical way to reduce the impact on the grid by reducing usage at a given time and avoiding new peaks. In a study in the Netherlands using solar photovoltaic generation, Chandra Mouli et al. (2016) examined the ability to charge vehicles at work. They attempted to maximize the solar energy usage through different charging profiles, which were chosen to align with an average photovoltaic generation profile. This shifting of electric vehicle charging loads to around midday was coupled with dynamic charging, i.e. using variable rather than fixed charging power, to better fit the photovoltaic curve. The capacity of local battery storage was also assessed to minimize grid dependence. The proposed system examined only a single vehicle charger, with three vehicles charged per day. This promising research is limited by the small sample.

In a study of the potential to shift electric vehicle charging loads, Babrowski et al. (2014) reviewed six European vehicle mobility studies and found no major differences between the charging curves described. They then used mobility data from Germany to give examples of potential load shifting benefits by decreasing the variability of the increased demand response and maximizing the use of photovoltaic energy generation.

2.3. Mobility models

A vehicle’s mobility model is used to describe its usage patterns, such as the distance travelled and the time of traveling. To model electric vehicle performance accurately requires accurate models of their mobility and the resulting electrical energy impact. This is especially true for the charging requirements. Quiros-Tortos et al. (2018) proposed a method to produce realistic electric vehicle profiles consisting of mobility and charging parameters. They warned that travel surveys can produce unrealistic demand profiles, as such surveys require assumptions to be made or use historic vehicle charging data that are often drawn from small unrepresentative datasets. This can further result in under- or over-estimations of charging impacts. Their model used probability density functions based on Gaussian mixture models to represent electric vehicle mobility characteristics. They evaluated their model against measured electric vehicle charging data. Comparing their model to other models based on surveys and trials, they found that the profiles it generated were not only realistic but described electric vehicle mobility more accurately.

A noteworthy study by Kara et al. (2015) estimated the potential benefits of smart charging for vehicles at non-residential locations. To apply and assess their smart charging strategy they used a large dataset from non-residential vehicle charging stations in Northern California. The strategy was to shift the charging period to make use of cheaper charging rates. The ability to shift the load was bounded within the period during which the vehicle was parked. The potential benefits they investigated were limited to the economics associated with two types of stakeholder: the owner of a charging service provider and the operator of the grid distribution system. In South Africa the stakeholders are grouped differently. The state utility Eskom serves as the generator, distributor and retailer in most situations, which means the stakeholder interest is often uniform.

To estimate the demand impact of electric vehicles at a regional level in the US, Harris and Webber (2014) developed a model based on national travel survey data and using Monte Carlo methods. They validated their model by comparing its charging behaviour to a small set of actual electric vehicle data. They investigated how unscheduled or uncontrolled charging could affect different regional peak demands. However, they considered only one charging scenario and did not consider any interventions to reduce the impact of the charging.

2.4. Contribution

The studies reviewed above, with the numerous models proposed, all discuss issues of carbon emissions, energy usage, load demand and cost. These issues are considered from one, or at most two, of three possible perspectives:

residential, commercial or energy supplier. However, none of the studies discusses all of those issues, or considers all three perspectives. Further, none of them takes into account a range of electric vehicle penetration, from small to medium, and large. This reveals a gap in the literature: at the time of writing no study had yet assessed the overall impact of electric vehicles charging on all parties involved.

Considerable research has been done on using solar energy to supplement vehicle charging (Leemput et al. 2014; Babrowski et al. 2014; Canizes et al. 2019) and some researchers have proposed using PV-equipped carports for this purpose (Chandra Mouli et al. 2016; Tulpule et al. 2013; Neumann et al. 2012; Nunes et al. 2016). However, such studies generally involve a scenario of a developed country with limited solar energy insolation. The scenario of a developing country with a financially constrained grid and abundant solar energy has not yet been considered.

In this study we examine the impact that electric vehicles will have in South Africa. We measure the carbon footprint, energy usage, load demand and cost impacts from the residential, commercial and energy supplier perspectives. Our carbon footprint analysis specifically looks at the CO_2 emissions associated to the operation of these vehicles. We assess a range of effects, from a one-vehicle owner to a large workplace or car park owner with a thousand vehicles to a million vehicles countrywide. We assess different charging scenarios on the basis of their impact, considering home and work based charging scenarios both separately and in combination. We consider how work-based charging with PV carports can make use of South Africa's abundant solar energy to reduce grid dependence and load.

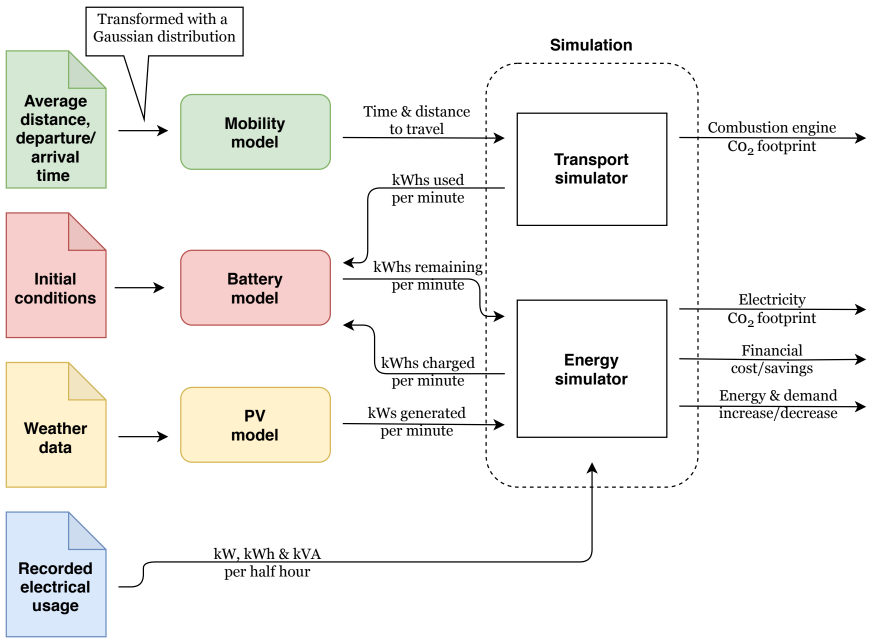


Figure 1: Simulation system diagram

3. Methods

The fundamental problem with charging an electric vehicle (EV) from a privately owned solar energy charger is that the vehicle owner will usually be obliged to charge it at night and therefore have to use another energy source or install battery storage to use the solar charger. Individual solar installations are bound to be more costly per kW_{pk} than a large solar farm. A solution is for large employers or car park owner (hence referred to as employer for simplicity) to sell electric vehicle owners solar energy at the workplace. Any shortfalls could be made up from the grid at a lower rate, as large employers typically buy cheaper electricity at bulk prices. A further advantage is that employers could use the surplus solar energy to offset their own demands. They could even use the electric vehicles' battery storage in a demand management application using a microgrid of vehicles.

This section covers three evaluation perspectives and scenarios, evaluated against petrol-fuelled vehicles, and the simulation models: the vehicle mobility model, the vehicle's battery model, and the solar photovoltaic (PV) generation model. The simulation setup, including the historic energy data, is depicted in Figure 1. The metrics used to assess the results in the charging scenarios are also discussed in this section.

3.1. *Perspectives and scenarios*

This paper explores the concept of workplace charging for privately-owned electric vehicles with three charging scenarios; (i) charging solely at home from the electricity grid, (ii) charging solely at work from grid-augmented PV carports, and (iii) a combination of these two, charging EVs at home and at work. A fourth scenario (iv) is, of course, to consider the situation of no EVs, with all personal transport utilising internal-combustion vehicles. These four scenarios have been examined from three perspectives; (1) that of the owner of the vehicle, (2) the perspective of the employer (assumed to be a large-scale employer), and (3) the perspective of the grid. The study focuses on the situation in South Africa, and we evaluate each perspective using vehicle fleet sizes of one, 1000 and 1 million EVs respectively. For each perspective we evaluate a combination of the following metrics: energy usage (and resultant CO_2 emissions), monthly peak demand, and financial costs. In the calculation of financial costs, we use the local municipal electricity tariffs (Stellenbosch Municipality, 2019) and the local regulated petrol prices (AA, 2019), both for the year 2019. We use South Africa's electricity carbon rates for the CO_2 calculations, as shown in Table 1.

3.1.1. *Perspective 1: EV owner with one vehicle*

Our owner has one vehicle, which is either a petrol vehicle or an electric vehicle. This owner cares most about their personal expense and carbon footprint. Our metrics for this perspective are therefore the cost of either refuelling the petrol vehicle or charging the EV, and the resultant CO_2 emissions. We calculate the refuelling cost of a petrol vehicle using the distance travelled at an average fuel usage of 6.3 L/100km and the prevailing petrol price (Posada, 2018).

It is the norm in developing countries to bill domestic electricity usage using a municipal meter that measures only aggregate energy used (Jack and Smith, 2016). To penalize heavy users and help poor users, the monthly billing uses a sliding scale rather than the time-of-use typically used in developed countries. On this scale the per-kWh rates increase with the total monthly usage, with the final tier activating when the monthly usage surpasses 600 kWh. A study by Goliger and Cassim (2018) demonstrated that South African households in the upper Living Standards Measure groups use more than 600 kWh each month, even without the additional load of an EV. In a developing country these households are likely to be the ones who will own EVs (Khan and Sinclair, 2016). We therefore use only the highest rate of the sliding scale to calculate the costs of charging an EV at home.

When charging at work, for our study, the EV owner pays the employer a fixed rate of 1.5 ZAR/kWh (0.094 USD/kWh). We chose this rate as being between the rate at which the grid supplier sells electricity and the rate at which it buys back electricity, benefiting both the employer and the employee.

We calculate the carbon emissions from charging at home from the grid using the total energy used and South Africa's average carbon intensity of electricity. Work charging causes emissions at the same rate; however, the energy considered is only what the EV absorbs from the grid. This means that losses in the inverting system incurred while charging at work do not contribute to the emissions in this perspective, and any solar energy used reduces them. To calculate the carbon emissions for a petrol vehicle, we use the amount of petrol used and the concomitant petrol CO_2 rate (U.S. Energy Information Administration, 2016).

3.1.2. *Perspective 2: Large employer with 1000 EVs and 1000 carports*

The large employer (we have used the example of Stellenbosch University) cares most about its finances and its carbon footprint. The monthly electrcity bill is determined mainly by the energy usage (kWh), the monthly peak demand (kVA), and the time-of-use (TOU) for each tariff period (kWh). Since the employer is defined as large, its usage has a consequential impact on the fragile grid. For the employer's perspective, we therefore consider the financial costs entailed, the carbon emissions, the energy usage and the monthly peak power demand.

Historic smart metered energy data from Stellenbosch University was overlaid with the simulated load from the 1000 EVs and the generation from the 1000 carports. The historic data include the apparent power, power factor and real power in 30-minute intervals.

The setup cost of the PV system and charging infrastructure are compared with the electricity bills and the income from selling electricity to charge employees' EVs. The cost of this system is calculated using a typical value of $14\,\mathrm{ZAR/W_{pk}}$ ($0.88\,\mathrm{USD/W_{pk}}$). We also use an infrastructure cost of R15, 008 ($938) for each charger (Nicholas, 2019).

To reduce the impact on costs and also assist the grid, in our simulation EV chargers are disabled during the peak TOU hours of 6 am to 9 am in winter, which is from June to August in South Africa. This schedule also ensures that the EVs' charge cycle overlaps better with strong sunlight, as Stellenbosch during winter receives daylight from around 7:30am to 5:30pm.

The employer's carbon emissions are calculated according to the net energy used when compared to the status quo base case in the absence of EVs. We therefore consider the impact on the grid of the additional burden of charging EVs compensated by the supplementary generation of the PV carports.

3.1.3. Perspective 3: The constrained coal-dependent grid with 1 million EVs and carports

South Africa's state owned utility, Eskom, is at the focal point of our grid perspective. Eskom cares most about its energy usage (i.e. the need for electricity generation), the resultant emissions for legislative purposes, and the peak demand.

To assess the impact on the grid, we overlaid historic data from the Eskom generation plants with the simulated impact of EV charging for the 1 million vehicles and PV generation for the 1 million carports.

In the base case only petrol vehicles are used, which is the effective status quo. For scenarios involving work charging of EVs, reduction of grid energy from PV systems is also taken into account. For the grid's perspective, we simulate a range of EVs on top of the historic data, to determine how many EVs are required to exceed Eskom's installed grid capacity.

3.2. Simulation setup

South African conditions were used to generate the EV mobility and charging data, and estimate solar energy potential data from solar PV carports. Figure 1 shows that the EV's mobility model affects the state-of-charge (SOC) of the EV's battery model, while the battery model records the total energy used when charging. The PV model's energy potential output reduces this total energy used, based on the charging strategy used. The charging strategies are investigated using the solar and EV data. The EV data also provide a way to compare EVs and petrol vehicles. The data are generated over a year with per-minute resolution.

3.2.1. EV simulation

The EV simulation creates output data for an EV fleet of a specified size. The model steps are daily increments, discharging and charging each EV that is active. EVs are set to be inactive during weekends and the Christmas holidays, resulting in no SOC changes. During the South African school holidays half of the EVs in a fleet are set to be inactive. These conditions are based on our focus on workplace charging, and account for the reduction in vehicles traveling to work during the holidays.

When EVs are actively in use, discharging occurs for trips made between home and the workplace, resulting in two discharge periods a day per EV. Recharging takes place at home, at work, or at both, depending on the scenario. Charging at home is done using a common fixed-power AC charger operating at 3.68 kW, while charging at work uses a proposed variable-power single-phase AC charger. The operating levels for the chargers are listed in Table 1. Both chargers are assumed to be 85% efficient, which is typical for these levels of AC charging (Kong, 2018).

Two aspects of the EV are modelled: the battery and its mobility. The battery model is based on a second-generation Nissan Leaf, and contains the following important parameters: capacity, SOC, range, usage efficiency and charging power levels. These parameters are specified in Table 1.

The mobility model is derived from a recent survey of the distance Stellenbosch University staff travel to campus. This model consists of a departure and arrival time, the distance covered and the time it takes to complete the trip. Each vehicle's travel distance is randomly sampled from a Gaussian distribution of the survey responses. An average work day of eight hours, from 8 am to 4 pm, serves as a basis for the departure and arrival time means. Each trip's departure and arrival time are randomly sampled from a Gaussian distribution around the mean arrival and departure times. The travel time is calculated from the travel distance and an average speed of $60\,\mathrm{km/h}$. We also incorporated holiday periods into the data, so that holiday travel is not included in the analysis.

The battery discharge depends on the distance travelled and the time of travel, while the charge depends on the time of travel and the battery's SOC.

Our proposed work-place variable power charger adapts its power delivery according to the EV battery's SOC and the amount of time remaining in the employer's car park. The combination of these two provides a measure of charge urgency. If an EV's SOC is below 30% and it cannot fully charge at work from the lower power level, the charger will operate at a higher power level for as long as necessary before reducing the power to ensure a charged vehicle is able to leave the car park for its journey home. The length of time an EV will charge at the respective power levels is calculated by

$$T_h = ((B_f - B_{\mathrm{SOC}}) - P_l * T_p)/(P_h - P_l) \tag{1}$$

$$T_l = T_p - T_h \tag{2}$$

where B_f is the full capacity of the battery, B_{SOC} is the current SOC, P_h is the high power charging level, P_l is the low power charging level, T_p is the duration that an EV is parked, T_h is the duration charging at P_h, and T_l is the duration charging at P_l.

3.2.2. Solar PV simulation

The solar PV generation is modelled with pvlib Python, which uses historic weather data to simulate the generated AC output power. pvlib Python was ported from PVLib MATLAB (Andrews et al., 2014), which was developed by Sandia National Laboratories (Sandia) as an open source PV modelling environment (Holmgren et al., 2018). We used per-minute weather data from a South African weather station [1] that includes solar radiation, wind speed and ambient temperature for a year. The Sandia PV Array Performance Model calculates the cell and module temperature, which provides a more accurate PV model, as the PV modules' performance is largely affected by temperature (Ozemoya et al., 2013). We use the six-parameter single-diode model developed by the California Energy Commission (Gilman, 2015) to calculate the module's DC output. The Sandia Inverter model simulates the AC power conversion by using King's empirical model (King et al., 2007).

The simulation requires the number of EVs in the investigated fleet as an input. Based on this input, it calculates the number of PV modules and inverters used. This number is determined by allocating a ratio of five PV modules to one carport, and a maximum of two carports to one inverter. The PV module and inverter manufacturer specifications used are listed in Table 1.

4. Results

4.1. Perspective 1: EV owner with one vehicle

Figure 2 shows the owner's perspective for each month of the year. These results are presented in absolute terms, to enable comparison with the petrol vehicle scenario. Figure 2a shows the carbon footprint in kg per month for the four scenarios, directly reflecting the energy used in each. We find that switching from a petrol vehicle to a charge-at-home EV substantially increases the owner's CO_2 footprint.

This startling finding is due to the coal dependent electricity generation in South Africa. The yearly aggregate, shown in Table 2, is a 23% increase, from 2251 to 2777 kg CO_2 per year. In fact, this is also the case for charging at both work and home, which results an annual increase of 10% despite the presence of PV augmentation at the workplace. It is only when work-place only charging is used that the carbon footprint reduces by 11% due to the high PV augmentation. The only exception is the month of May, during which charging only at work results in a slightly higher footprint than that of using a petrol vehicle – 220 kg versus 208 kg. It is, however, trivial to avoid this exception by also including May in the winter charging schedule.

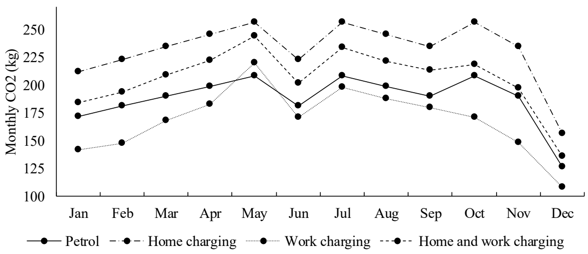
Figure 2b shows the resulting financial impact on the owner for the same period. It is clearly more expensive to refuel a petrol vehicle than to charge an EV, and it is cheaper to charge an EV at work than at home. This is why charging at both work and home is the second cheapest option. It can be concluded, from both carbon footprint and financial aspects, that charging an EV only at work is by far the best option.

Note that energy plots are not explicitly shown for the three perspectives, as they are equivalent to the carbon footprint plots provided, with the exception that petrol vehicles do not contribute to any electrical energy usage.

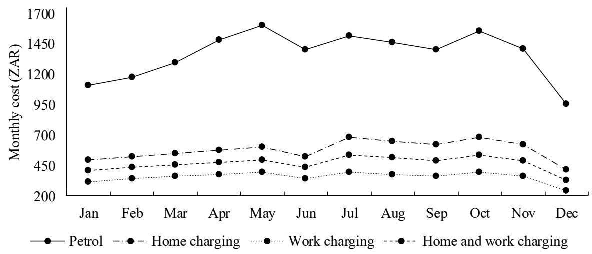
[1] Stellenbosch Weather Station: http://weather.sun.ac.za/

Table 1: Parameters used in the simulation setup

Parameters	Value	Units	Source
Battery model			
Battery capacity	40	kW h	(Nissan)
Travel range	240	km	(Nissan)
Efficiency	16.6	kWh/100 km	(Nissan)
Low charging power, P_l	6.67	kW	
High charging power, P_h	3.68	kW	
Mobility model - Gaussian			
Work arrival time			
Mean, μ	0	min	
Standard deviation, σ	7.5	min	
Work departure time			
Mean, μ	0	min	
Standard deviation, σ	7.5	min	
Distance			
Mean, μ	30	km	
Standard deviation, σ	10	km	
Carbon emissions			
Carbon intensity of electricity	954	kg CO_2/MWh	(Eskom, 2019)
Carbon intensity of petrol	2.3	kg CO_2/L	(U.S. Energy Information Administration, 2016)
PV modules			
Maximum power	330	W	(Canadian Solar, 2018)
Max voltage	37.2	V	(Canadian Solar, 2018)
Max current	8.88	A	(Canadian Solar, 2018)
Open circuit voltage	45.6	V	(Canadian Solar, 2018)
Short circuit current	9.54	A	(Canadian Solar, 2018)
Tilt angle	15	°	
Azimuth	0	°	
Inverter			
Maximum usable DC power	4200	W	(SMA)
Maximum AC output power	4000	W	(SMA)
CEC efficiency	97	%	(SMA)



(a) Carbon footprint



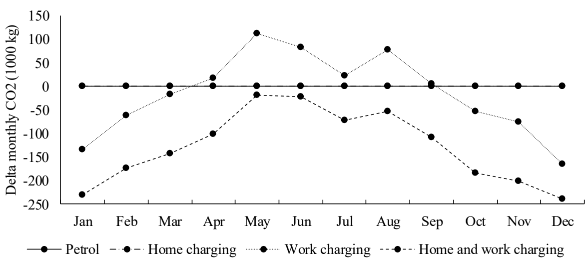
(b) Financial costs

Figure 2: EV vehicle owner perspective with one EV.

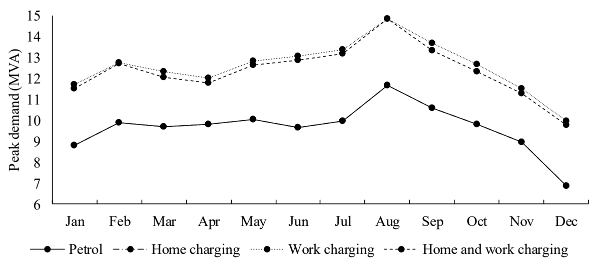
4.2. Perspective 2: Large employer with 1000 EVs and 1000 carports

Figure 3 presents the results from an employer perspective for the four scenarios. These results are provided relative to the baseline case, since the absolute results will differ for each employer. Figure 3a shows the difference in carbon footprint from the measured baseline of the employer's buildings. There is no impact from the employer's perspective for either petrol vehicles (the baseline case and status quo) or EVs charging only at home. EVs charging only at work with augmented solar generation produce resultant negative CO_2 emissions for the sunny months of the year, September to March. When these EVs are allowed to also charge at home, the resulting carbon footprint is negative throughout the entire year. This is because EVs charging at both locations will charge less at work, allowing more of the energy generated from the PV system to be fed back into the buildings and reducing the employer's overall grid energy usage. The results in Table 2 show that both scenarios on a yearly aggregate are net negative, with the combined work-and-home charging scenario producing a reduction of 1.5 million kg of CO_2. In terms of the employer's carbon footprint, EVs that also charge at home are the best option.

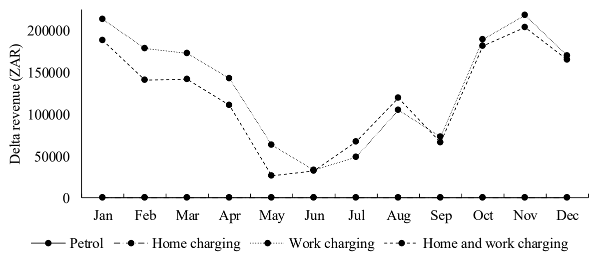
Figure 3b shows the historic monthly peak demands and the new peak demands from the charging scenarios. When EVs also charge at home, the monthly peak demand is smaller than that for EVs charging only at work. The difference between the two new peaks is in the order of a few hundred kVA. For an employer wanting to provide EV charging but concerned about the peak demand increasing, work-and-home EV charging is the best fitting scenario.



(a) Carbon footprint

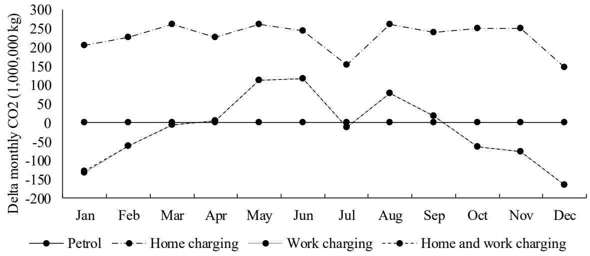


(b) Peak demand

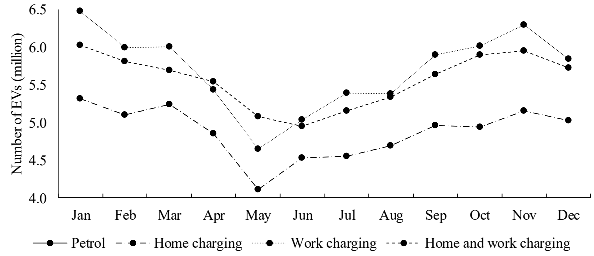


(c) Revenue

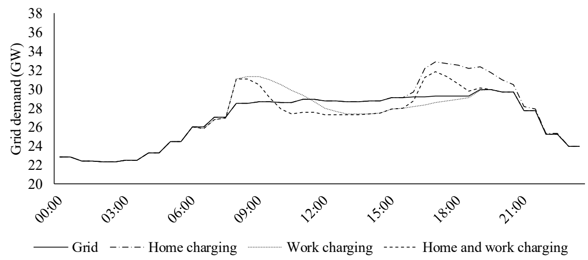
Figure 3: Employer perspective with 1000 EVs and 1000 carports.



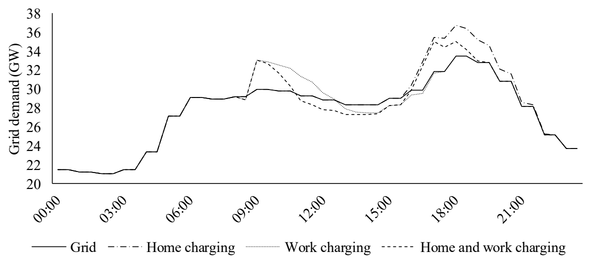
(a) Carbon footprint



(b) EVs required to exceed the grid's capacity



(c) January daily profile



(d) June daily profile

Figure 4: Grid perspective with 1 million EVs and 1 million carports.

Figure 3c shows the financial impact on the employer. The employer is able to make a larger net revenue from EV owners charging only at work, with the exception of the months of July and August. As shown in the figure, the profit from work-and-home EV charging follows the work-only charging. The yearly aggregate results in Table 2 show that charging EVs only at work yields 12% more revenue.

4.3. Perspective 3: The constrained coal-dependent grid with 1 million EVs and 1 million carports

Figure 4 shows the impact from the grid's perspective. These results are presented as absolutes. Figure 4a shows the grid's carbon footprint and demonstrates that charging EVs at home produces the biggest carbon footprint, while both work-only and work-and-home charging produces the smallest. This is because we consider that all the energy produced from the PV carports will reduce the total grid energy required.

Figure 4b shows the number of EVs required to exceed the grid's capacity in the different EV charging scenarios. This is especially important, given South Africa's fragile utility. The grid's capacity is exceeded with the addition of 4.11 million vehicles (an estimated 37% of the total fleet) charging only at home in May. It takes 5.32 million vehicles charging only at home to break the grid in this scenario's best-case month of January (which happens to be when Eskom resumed load shedding in 2020, even with virtually no electric vehicles in the country). Work-and-home charging performs slightly better – it takes 4.65 million and 6.48 million vehicles to break the grid in May and January respectively. In the best-case scenario, charging only at work, the grid can sustain between 4.95 million and 6.03 million vehicles throughout the year.

Figure 4c and Figure 4d show daily demand profiles for a summer and a winter month respectively. A morning and an evening peak are apparent above the historic profile. The morning peaks in these plots are from the work-only and work-and-home-charging scenarios, while the evening peaks are associated with the home-only charging scenarios. As shown in these figures, work-and-home EV charging contributes to both peaks; however, the duration of these peaks is much shorter than those in the other scenarios. Figure 4d shows how, in the winter based charging schedule used to avoid peak times, EVs begin charging only after 9am. Home-only EV charging contributes to the largest overall demand in a day, which is in the evening. The morning peak that occurs in both months is followed by a dip, which is a result of the energy supplied by the PV systems. This dip reveals an opportunity to balance EV charging across the day by spreading out their charging towards the afternoon, to make use of as much available PV energy as possible, and reduce these morning peaks further.

Table 2: Simulation results in yearly aggregates

Perspective	Metrics	Petrol	Home	Work	Work & home	Unit
Owner (absolute)	CO_2	2,251	2,777	2,021	2,472	kg
	costs	16,368	6,951	4,262	5,611	ZAR
Employer (relative)	CO_2	0	0	-189,000	-1,545,000	kg
	revenue	0	0	1,607,000	1,441,000	ZAR
Grid (absolute)	CO_2	2,209,642	2,725,665	-185,422	-179,743	10^3 kg

5. Conclusion and future work

At the time of writing we could find no previously published literature that had investigated the impact that electric vehicles could have on their owners, their employers and a carbon-heavy and constrained generator in a developing country, and at the same time also assessed the possible carbon emissions, energy consumption, load demand and associated financial costs. This paper presented an evaluation of these perspectives and metrics and considered how the time of charging can affect the use of solar energy, thereby reducing the negative implications of electric vehicles in this situation.

We assessed the electric vehicle perspectives in quantities of one, 1000 and 1 million vehicles. Each simulation was run with scenarios of vehicles charging at home, vehicles charging at work and vehicles charging at both home and work. The work scenarios used photovoltaic (PV) carport charging to reduce grid usage. This PV modelling used measured weather data to produce accurate results. In all cases, the simulation generated daily travel data and per-minute energy consumption data for the period of a year, providing information to compare the impacts of electric vehicles and traditional petrol vehicles.

Our results showed that from a vehicle owner's perspective it is significantly more expensive to refuel a petrol vehicle than it is to charge an electric vehicle, and that electric vehicle owners are able to save the most by charging their vehicles at work. For South Africa, carbon emissions from charging the vehicles increase beyond those of a petrol vehicle in almost every case, except when the vehicles are charged solely charge at work, making the most use of solar energy.

From the employer's perspective, at-work charging scenarios have an annual net positive revenue and a negative carbon impact. The financial benefit is larger when employees charge only at work. The overall carbon emission footprint is smaller when employees also charge vehicles at home, as less charging takes place at work, allowing excess solar energy to be fed back into the building.

As in the other two perspectives, the grid is put under the most pressure from electric vehicles charging only at home. The carbon footprint is higher, and the energy capacity of the grid is exceeded with the addition of 4.11 million of these vehicles. The projected daily demand profile shows a morning peak when vehicles are charged at work and an evening peak when they are charged at home. When the vehicles are charged at home and at work, the duration of the peaks is shorter. These findings suggest the need to investigate how to balance electric vehicle charging times further and reduce these peaks.

Our investigative study of the impact of a growing electric vehicle fleet in South Africa makes it clear that the arrival of these vehicles must be planned for beforehand. If not, their associated carbon footprint will be larger than that of petrol vehicles they replace, defeating the purpose of changing to electric vehicles. Without this planning, they will also placing a large strain on an already struggling grid. Solar PV carports at the workplace will reduce the impact on the grid, save costs, and decrease the carbon footprint. It is likely that owners will also charge their electric vehicles at home, so it is important to incentivize them to use the most viable and sustainable balance of home and work charging.

Since our focus was the electrical and environmental impact of the impending introduction of EVs, we limited our environmental assessment to operational life-cycle of the vehicle. We therefore excluded the environmental impact of pre-operational production and shipment and post-operational disposal. For future work assessing and comparing the full life-cycle environmental impact of combustion engines and electric vehicles to support owners' selection, these need to be included for both types to support vehicles.

Overall, the study has shown that work-place charging of EVs using PV augmented carports, whether it is the sole charging scenario, or if it is combined with home-based charging, has significant benefits, including an overall reduction in total carbon footprint, and an increase in the total number of EVs that can be supported by the grid. A further benefit is the potential income stream generated for the workplace. The real benefits stem from the fact that PV generates in the daytime, and if EVs are at the workplace during the day, then it makes excellent sense for them to be charged there, providing direct and local consumption of the solar-generated electricity, managing an increased overall load on the electricity system from the growth in EV numbers, without the need for increased centralised resources and grid capacity. This is true even for a carbon-based electricity system such as that in South Africa.

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