Using System Dynamics Modelling to Determine the Impact of Charging Electric Vehicles on the Hourly Load Profile and Household Costs

Nalini Sooknanan Pillay
Eskom SOC, Research Testing & Development
Private Bag 40175, Cleveland, 2022, South Africa
Email: pillayna@eskom.co.za

Andries Botha
Toyota South Africa Motors
P O Box 481, Bergvlei, 2012, South Africa
Email: abotha@alum.mit.edu

Abstract:
In South Africa, there was an increase of 80% more electric vehicles (EVs) being purchased in 2022 compared to 2021. These are passenger vehicles which are assumed to be charged in households in the residential sector. Electric vehicle purchases would be dependent on a variety of factors, which in many countries may include factors such as incentives, retail prices, market availability, maintenance costs, carbon taxes, fuel costs and vehicle efficiency. In South Africa, the shortage of electricity and the increasing electricity tariffs are perceived to be critical in influencing potential EV purchases. This research was based on the premise that a more expensive tariff during peak demand periods would likely change customer behaviour to charge during off peak periods. It was also undertaken to quantify the impact on household electricity consumption and costs with EV charging at home. A system dynamics simulation was developed in order to explore the dynamics. Results indicated that there was a clear financial incentive to move charging away from peak tariff periods to off-peak, however, it is likely that there will be households where tariffs as a load shifting tool, may not be effective. These are the households where disposable income does not present restrictions because their investments and income are significant.

Keywords: System dynamics, electric vehicles, household electricity consumption, load profile

INTRODUCTION

The distribution profile of electricity consumption In South Africa indicates that the largest consumer is the industrial sector at 56%, followed by the residential sector at 19%, and then the services sector at 14% (Cowling, 2023). This means that any dynamics that affect the electricity consumption in these sectors would have to be well understood so that network loads are anticipated and managed in order to mitigate against grid constraint problems and to be able to plan for demand. With the electricity tariffs increasing year on year, and due to persistent loadshedding in the country, the prolific adoption of electric vehicles (EVs) in the current economic climate presents uncertainty. Mitigating against the effects of greenhouse gas emissions has presented a global challenge, with changes to modal transport specifically electric vehicle (EV) substitution of the internal combustion engine vehicles seen as one mechanism to attain a zero-carbon emission future.

This research was based on the premise that households in the residential sector are likely to optimise expenditure on electricity consumption and this may impact the migration of consumers towards electric vehicles away from internal combustion engine vehicles (ICEVs) (due to charging at home), as well as the times at which EV owners charge their EVs. This in turn means that the load profiles for households would change and may require load management strategies. System dynamics modelling was used to build a simulation to run various scenarios and understand the impact on cost and electricity consumption based on time-of-use charging.

BACKGROUND

Road transport has been identified as being the largest source (>90%) of greenhouse gas (GHG) emissions within the transport sector in South Africa (Omarjee, 2020). Despite initiatives to improve vehicle efficiencies, the use of alternative fuels and a shift to other mobility solutions, transport emissions have continued to increase (ITF, 2019).

South Africa pledged to introduce mitigation efforts to reduce emissions as per the 2015 Paris Agreement, as have other countries in global efforts to decarbonise the economy. The country's Green Transport Strategy was drafted to include strategies that would support efforts to reduce greenhouse gas (GHG) emissions, which also includes a move away from the Internal Combustion Vehicles (ICEVs) to the adoption of electric vehicles (EVs). It was proposed that transport transition levers and measures could either be modal (changes in mobility options) and/or energy related changes to energy use and the energy mix in transport (Ahjum, Godinho, Burton, McCall, & Marquard, 2020). The constitution of the vehicle parc and the choice of vehicle would, however, be dependent on a variety of factors which in many countries may vary from incentives, retail prices, market availability, maintenance costs, carbon taxes, fuel costs, range anxiety and vehicle efficiency. In South Africa, there are additional dynamics which may influence the purchase of electric vehicles such as:

1. **Loadshedding:** these are controlled processes which respond to unplanned events in order to protect the electricity power system and results in planned power outages for short periods of time. The South African grid has experienced unprecedented pressure due to rapid urbanization, growth in mining and the industrial sector, as well as aging coal power stations, delayed maintenance and inadequate new capacity which have resulted in these power outages/ loadshedding events. This means an interruption in charging EVs during the loadshedding periods, which has then made prospective EV owners question the decision on whether to migrate from ICEVs to EVs. While EV owners would be concerned about electricity availability, the electricity utility would be concerned about additional demand that would be introduced by EVs being charged in the household sector, thus necessitating this study.

2. **Rapidly increasing electricity tariffs:** Figure shows the overall average increase in electricity tariffs in South Africa from 1988 to 2022 plotted against the Consumer Price Index (CPI) (Moolman, 2022). Currency unit is the South African Cents (ZAR Cents).

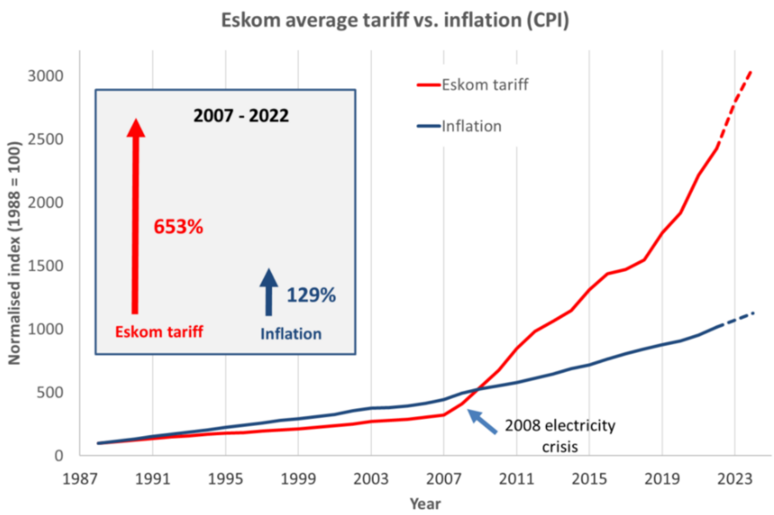


Figure 1: Eskom tariff versus Inflation from 1988 until 2022 (Moolman, 2022)

During the first period from 1988 until 2008 (when South Africa experienced the first electricity crisis), the Government policy ensured that electricity tariffs were kept low for low-income households and since there had been an oversupply in electricity in the 1990's. From 2007 until 2022, electricity tariffs increased by 653% whilst inflation increased by 129%. In other words, electricity tariffs quadrupled over a 14-year period. The electricity utility, Eskom, then applied to the National Energy Regulator of South Africa (NERSA) to restructure the tariffs to protect lower-usage residential customers from high price increases and to also temper heavy electricity users. The new structure for residential customers, known as the Homeflex tariff (price of electricity changes according to the time of day) as opposed to the Homepower tariff (block charges based on usage), was deemed suitable for medium- to high-usage residential urban customers, who were able to shift load from the expensive peak periods to the less expensive off-peak periods. In view of the changing tariff structure, the question that remained to be answered was what the impact of charging EVs would be on the on the load profile during peak times and what the cost implications for the consumer would be.

Due to the high household costs with the increase in electricity tariffs, we needed to understand if South Africans in the different income groups would be able to afford to charge their EVs. With South Africa's Gini coefficient of 0.67, affordability is a very important consideration in purchasing EVs (Valodia, 2023).

3. **Energy prices:** It was observed that the increased energy prices also influenced the sales of EVs and ICEVs in South Africa. **Error! Reference source not found.** shows the price trend for petrol and diesel from 2010 until 2023 in South Africa (Department of Mineral Resources & Energy, 2023). Currency unit is the South African Cents (ZAR Cents).

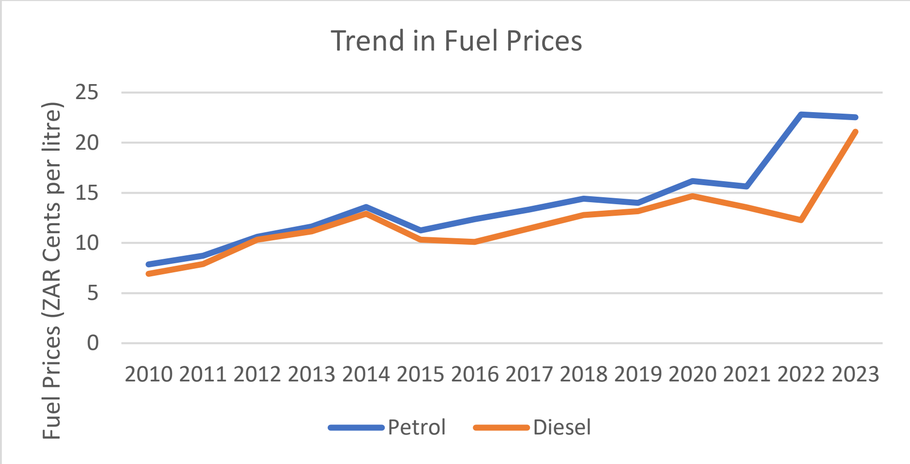


Figure 2: Price trend of petrol and diesel in South Africa (Department of Mineral Resources & Energy, 2023)

The EV volumes in South Africa according to various powertrains is shown in Figure with a clear increase in EV purchases in 2022 and 2023 (Woosey, 2023) (Bubear, 2024). BEV are the fully battery electric vehicles, HEV refers to the conventional hybrid electric vehicles and PHEV refers to plug-in hybrid electric vehicles. Based on this trend, the expectation is a position steep incline in electricity consumption of up to 60 TWh by year 2050 (ZeroCarbon Charge, Malherbe, & Roux, 2024).

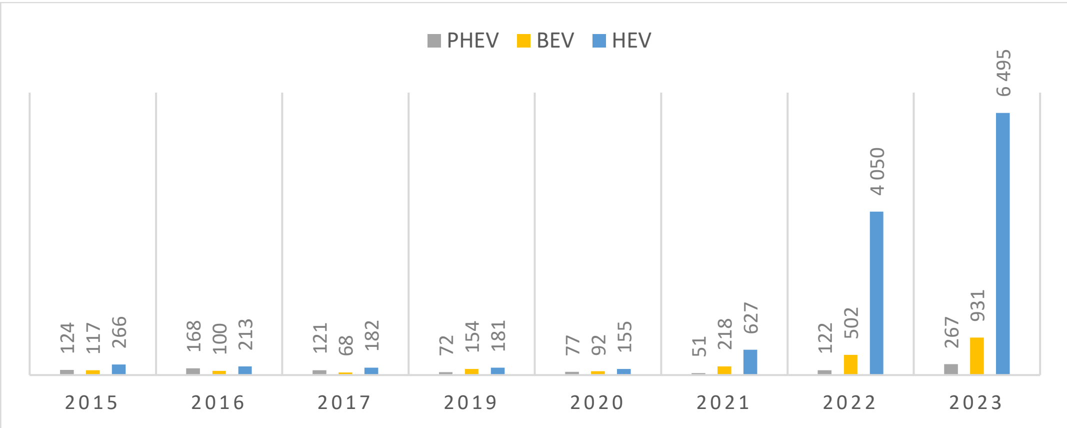


Figure 3: Electric vehicles in South Africa (Woosey, 2023) (Bubear, 2024)

The National Income Dynamics Study (NIDS) in South Africa defines socio-economic classes based on a household's potential to have opportunities to grow or if they are at risk or vulnerable to dropping to lower income levels (SA-TIED, 2019). The five social classes and the fraction of the population per class as well as: Quintile 1 (Q1) - Chronically poor (7,524 mill households); Quintile 2 (Q2) - Transient poor (1,655 mill households); Quintile 3 (Q3) - Vulnerable middle class (2,257 mill households); Quintile 4 (Q4) - Stable middle class (3,010 mill households); and Quintile 5 (Q5) – Elite (0,602 mill households).

In this study, it is assumed the Quintile 4 (stable middle class) and Quintile 5 (elite) are likely to be able to afford EVs based on their disposable incomes. The general rule of thumb is that 25% of the monthly salary is allocated to transport/ vehicle costs (Business Tech, 2021). The annual salaries for the various social classes was obtained (Adeaga, 2022) and based on 25% allocated to vehicle purchases, the size of vehicle was ascertained. This means that Quintile 5 would be able to afford small, medium and large cars (Minimum Monthly Income (>110,820 Rands)); and Quintile 4 would be able to afford small and medium vehicles (Minimum Monthly Income (>110,820). The Nissan Leaf was selected for a small car (40 kWh battery capacity, average range 200 km), and the Renault Megane E-Tech EV60 220hp as a medium car (60 kWh battery capacity, range 320 km) (EV Database, 2023).

Simulator runs were conducted to determine the difference in costs between households in the different income quintiles using the Homepower 1 block structure (Table 1) when compared to the time-of-use (TOU) Homeflex tariff structure (Table 2).

Table 1: Homepower (Block) Tariff Values (ZAR Cents per kWh)

	Block 1	Block 2
	(0-600 kWh)	(>600 kWh)
Homepower 1	253,54	400,33

Table 2: Homeflex (Time-of-use) Tariffs (ZAR Cents per kWh)

	High Demand ZAR Cents/ kWh	Low demand ZAR Cents/ kWh
Peak	624.21	204.4
Standard	189.91	141.04
Off-peak	103.7	89.92

METHODOLOGY

Spreadsheets can assist in organizing data points and generating historical performance metrics for reporting purposes but does not assist decision makers in understanding the inter-relationship between variables and the conceptual architecture associated with dynamic complexity (Hennessy, 2016). With system dynamics models, a visual representation exists of the inter-relationship between variables, which allows engagement of the model by the user and the relevant stakeholders.

Due to the hundreds of variables that were used in the computations and the model, the iSee Stella model layer assisted us in explaining the inter-relationships between the variables with our stakeholders and also helped minimize the number of equations we would have had to program (as would have been the case in Excel).

The system dynamics modelling software used was iSee Stella Architect and the time resolution was hourly over 744 time units (equivalent to a month). Figure shows EV charging. The completed model is much larger but for this paper, the EV charging model will only be explained.

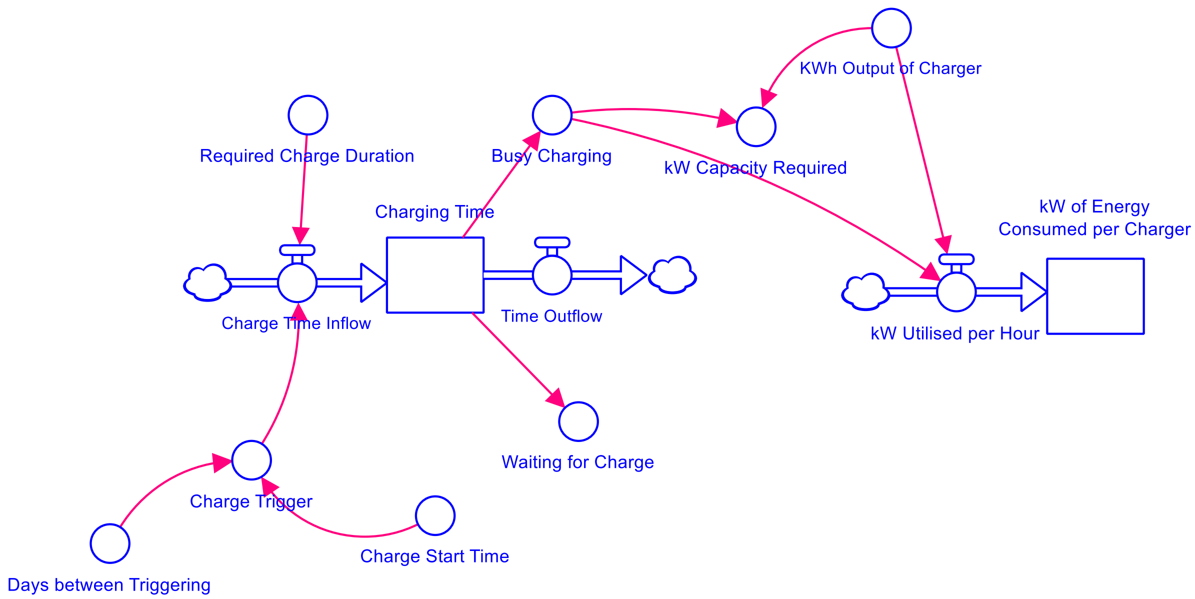


Figure 4: EV charging model structure

In order to replicate the anticipated demand pattern of a consumer owning an electric vehicle the control theory basis of system dynamics was used. The basic charging switch design demonstrates how a particular user charges his or her vehicle. While no feedback loops are shown in the charging switch model, the obvious feedback loop would include the battery charge status. As the vehicle gets used, the energy stored in the battery is utilised. As the battery drains down, the owner can decide when a charge is required. The current design of the charge switch assumes that the owner does not want to keep the charge in the battery as high as possible at all times, but rather only charges the battery once a lower limit has been reached. The battery will then charge for a longer duration at less frequent intervals.

In summary, the charging switch will simulate the behaviour of an owner of an electric vehicle that charges the vehicle for a fixed amount of time, starting at a specific time every time on regular intervals that can exceed one day. In the demonstration case the following is assumed:

Charge Start Time: 7:00 PM or 19:00
Required Charge Duration: 6 hours
Days Between Charges: 3 days
Starting Day: 0 – reflecting the start of the simulation run

The charging switch structure is a single stock model that keeps track of the number of hours that the battery needs to be charged for. This function could be replicated by a state variable, but that will introduce the inflexibility of a fixed repeating pattern. By using a stock – Charging Time - to keep track of the time needed for charging, both the amount of time required and the frequency of charging can be varied by changing the values in 2 converters. It also makes the structure sufficiently flexible to add the feedback loop from real battery usage. When the Charge Trigger has a value of 1 then total value of Required Charge Duration flows into the Charge Time stock. As long as the Charging Time is greater than 0, the battery of the electric vehicle will be charged as indicated by the Busy Charging converter. Multiplying the capacity of the charger as the converter kWh Output of Charger by the Busy Charging signal the total energy consumed by the vehicle battery can be calculated. The total amount of energy consumed is calculated in the stock kW of Energy Consumed. The approach allows the utility company to see both the peak capacity required as well as the overall demand.

The Charge Trigger converter calculation requires the user to select the time of day at which the vehicle will be plugged in and the charging must start. Charge Start Time uses a 24-hour clock to simplify calculation and is set at 19 to reflect 19:00 or 07:00PM. The second element is the Days Between Triggering converter which has been set to work in days and not hours. The calculation of the Charge Trigger adjusts any day values to a 24-hour cycle. The final converter needed for the calculation is the Starting Day converter that reflects the day on which the first charge is required.

The calculation in the Charge Trigger uses the PULSE built-in functionality of STELLA Architect. The following equation is used:

Charge Trigger = PULSE(1, Charge_Start_Time+Starting_Day*24, (Charge_Start_Time+24*Days_between_Triggering))

The PULSE function allows the inflow to the stock to be triggered at regular intervals on the 24-hour clock. The same functionality can be achieved using the STEP built-in function in STELLA. The STEP function will reduce the model to a converter only model which does not show how the time runs down.

Using the STEP function the following equation is required:

Charge Trigger 2 = STEP(1, Charge_Start_Time+Starting_Day*24, Required_Charge_Duration, Days_between_Triggering*24)

While functionally the same, the use of a stock adds a visual element that the converter on its own does not achieve and the Charge Switch can be replicated in other software systems that does not contain the same built-in functionality. Of course, a series of converters using the COUNTER built-in function can also be used to achieve the same result.

RESULTS & DISCUSSION

The assumptions used: daily charging, with a small EV battery size for Quintile 4 and a medium EV battery capacity for Quintile 5. The other assumption was that the car battery still had residual charge of 35% in the small EV battery and 40% in the large EV battery when plugged in at home. A Level 1 AC charger (3.7 kW) was used for Quintile 4 which meant a charging time for the small EV battery of 7 hours. A Level 2 AC charger was used for a medium EV battery capacity for Quintile 5 which meant a charging time of 2 hours. Figure shows the change in load profile depending on the type of home charger.

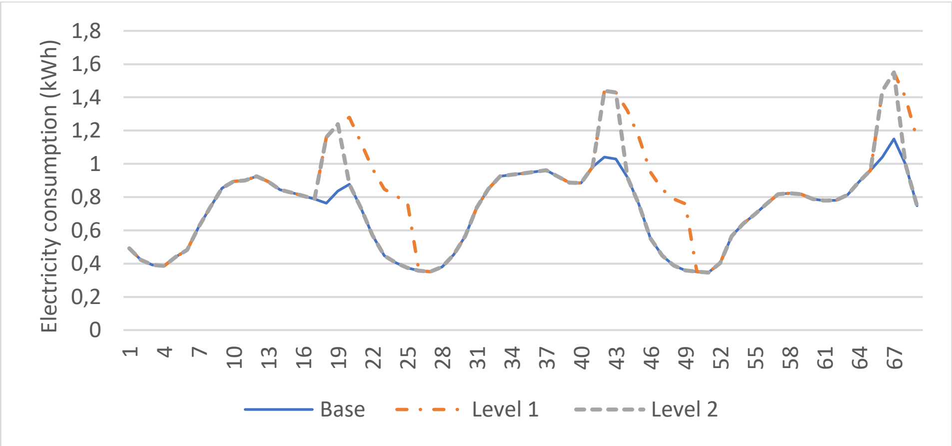


Figure 5: Electricity Consumption profile change due to type of EV charger

Figure shows the single household consumption for Quintile 4, with and without BEVs and Figure shows Quintile 5. The calculations assumed daily charging at 6pm. The highest consumption months are June and July and the lowest is January and February.

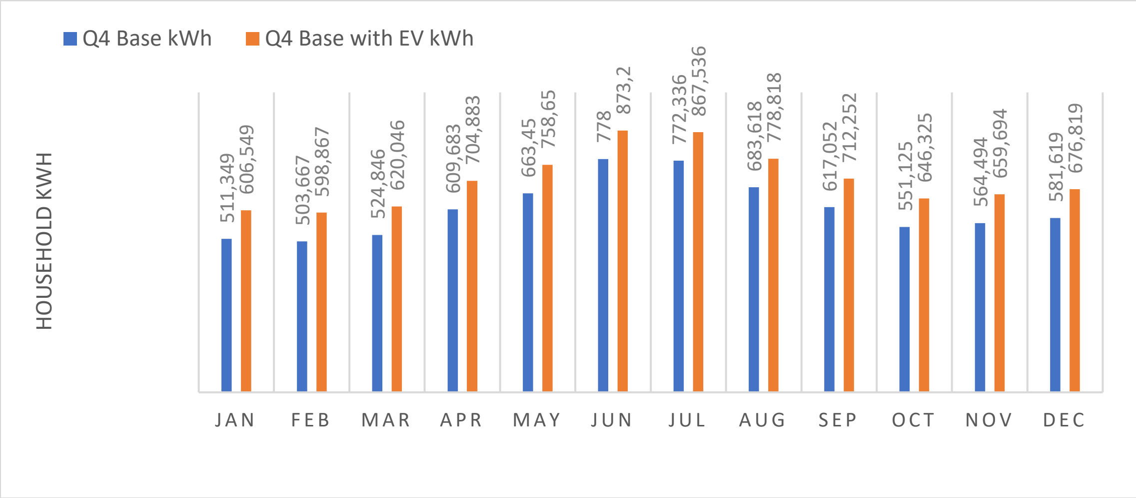


Figure 6: Quintile 4 Household consumption with and without BEVs

Results for Quintile 4 show an increase of 576 kWh per year. Based on the base annual consumption of 7,361 kWh per year for Quintile 4, this is an increase of 7.82% in the electricity consumption for the year.

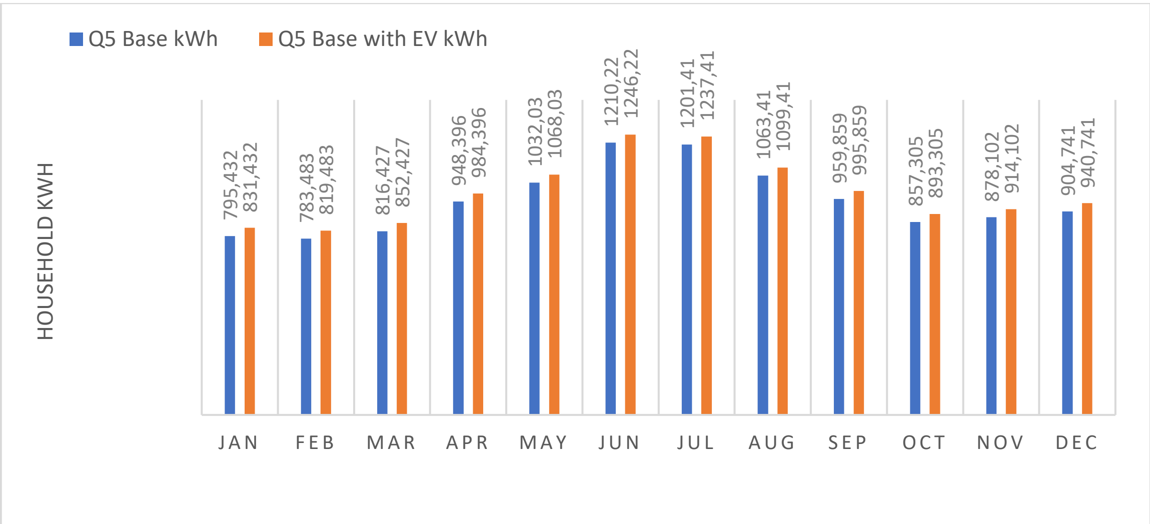
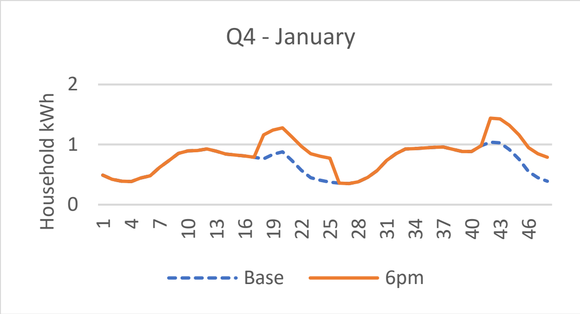


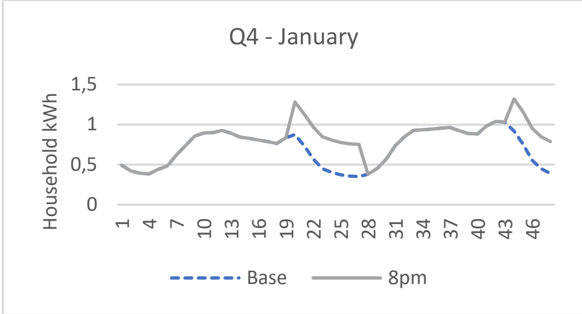
Figure 7: Quintile 5 Household consumption with and without BEVs

Results for Quintile 5 show an increase of 864 kWh per year. Based on the base annual consumption of 11,451 kWh per year for Quintile 5, this is an increase of 7.55% in the electricity consumption for the year.

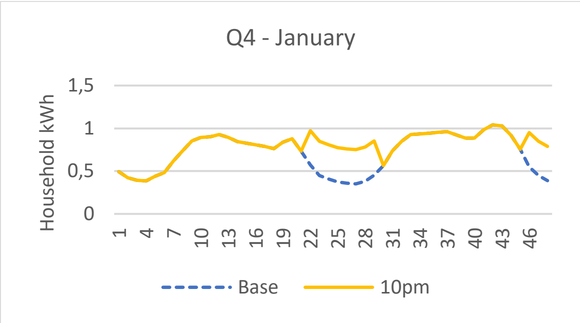
Figure shows the impact of varying the daily charging start times on a Quintile 4 load profile, assuming a small EV battery capacity.



(a) 6pm



(b) 8pm

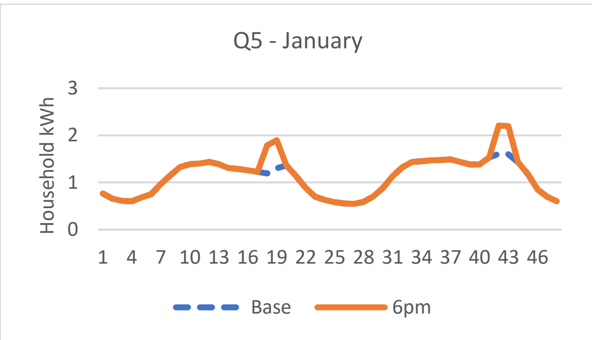


(c) 10pm

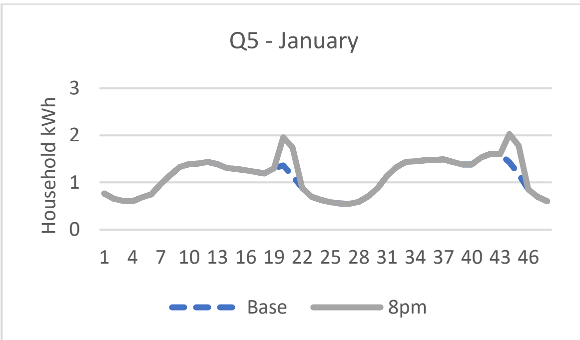
Figure 8: Quintile 4 Load profile with varying EV starting charge times

Visually it is clear that charging at 10pm and at midnight would reduce the peak, however, would a financial driver be sufficient to change the behaviour when it comes to charging times by EV owners. This dynamic was the explored later on.

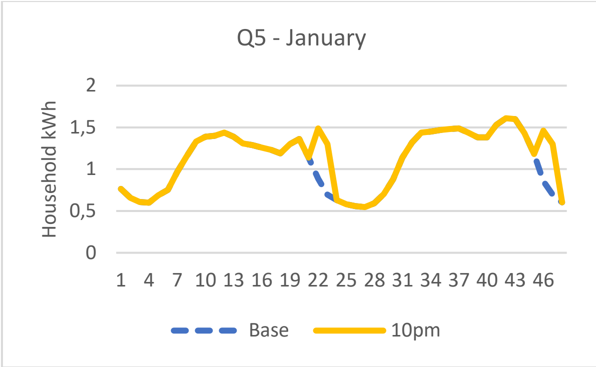
Figure shows the impact of varying charge start times for Quintile 5 – assuming a level 2 charger (shorter charging times).



(a) 6pm



(b) 8pm



(c) 10pm

Figure 9: Quintile 5 Load profile with varying EV starting charge times

Based on the above profiles, visual inspection shows that 6pm and 8pm charging are still in the peak demand times.

In terms of the additional electricity costs in South African Rands (ZAR) due to charging EVs at home, Figure 0 shows the cumulative monthly values at the different charging times for Quintile 4 and Figure 12 shows the results for Quintile 5.

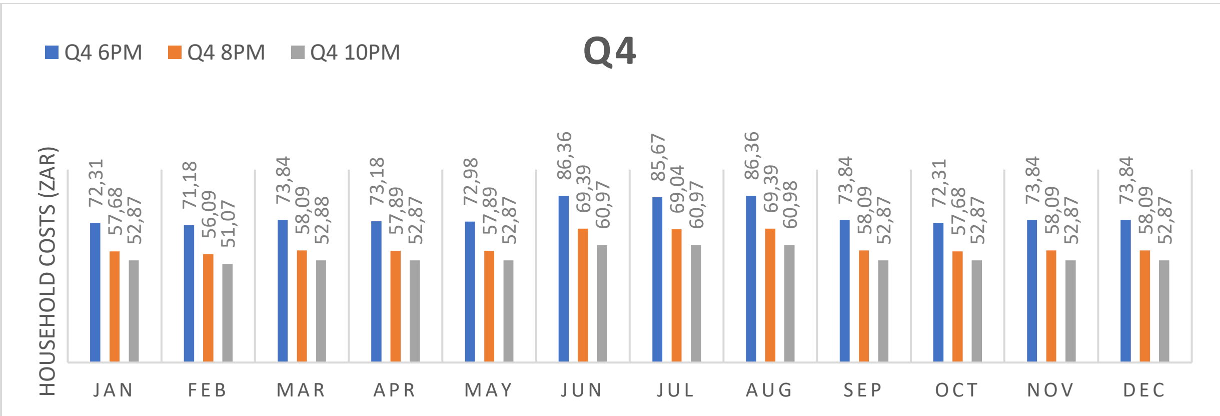


Figure 10: Quintile 4 EV household costs based on Homeflex tariffs over a month

When looking at the difference between 6pm and 8pm charging or 6 pm and 10 pm charging, there is a saving. However, the additional costs when charging at 8 pm versus charging at 10 pm is very small. Using January as an example, moving from charging at 6 pm to 8 pm means a saving of ZAR14.99 while moving from 8pm to 10pm means a saving of ZAR72 cents. It would be expected that charging at 10 pm would provide no real financial incentive for EV owners and they would likely go for a cheaper tariff period at a convenient time which is then 8pm charging. The additional annual electricity costs due to EV charging is approximately ZAR430.80 in a Quintile 4 household.

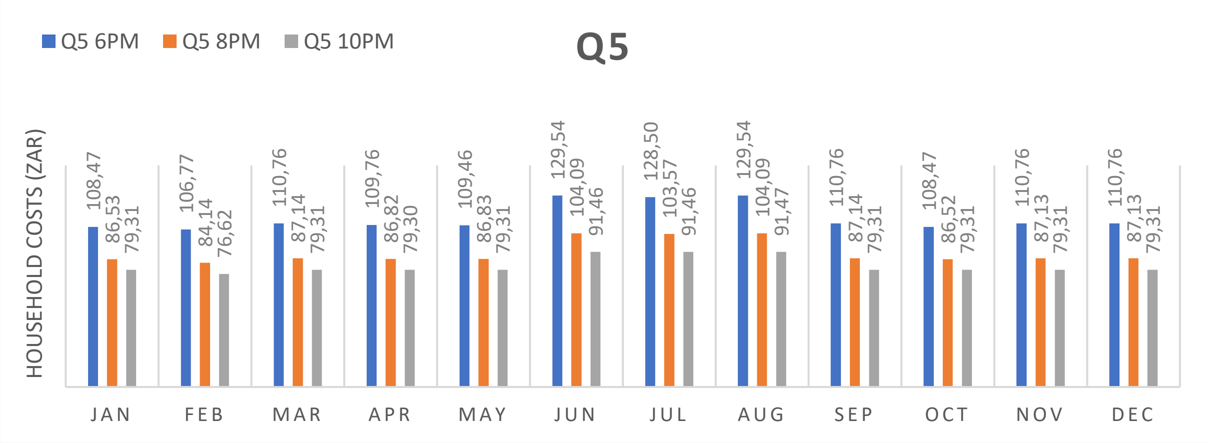


Figure 1: Quintile 5 EV household costs based on Homeflex tariffs over a month

Based on the results for Quintile 5, the cheapest charging time is at 10pm. If charging takes place at 8pm instead of 6pm, there could be a savings of about ZAR15 per month or ZAR3.70 per week. Charging at 10pm instead of 8pm means an additional savings of ZAR6.14.

Table 3 shows the difference in additional household costs due to EV charging between using the Homepower (Block) tariff and the Homeflex (TOU) tariff for Quintile 4 over a period of a week and for Quintile 5.

Table 3: Homepower (Block) Tariff Values (ZAR Cents per kWh)

Scenario	Quintile 4 Annual Household Costs in ZAR	Quintile 5 Annual Household Costs in ZAR
Base Homeflex	2,798	4,352
Base Homeflex with EVs	3,097	4,511
Difference between Base Homeflex and Base Homeflex with EVs	299	159
Base Homepower	6,340	10,252
Base Homepower with EVs	7,215	10,651
Difference between Base Homepower and Base Homepower with EVs	875	399

Results indicate that EV owners are likely to pay almost four times more on the Homepower block tariff than when using the Homeflex TOU tariff structure. The reason why the Quintile 4 has more EV costs than Quintile 5 is because of the Level 1 charger in Quintile 4 which means longer charging times.

CONCLUSIONS

The annual base consumption for a single household in Quintile 4 is 7,144.11 kWh and for Quintile 5 is 11,113.3 kWh.

For a single household, Quintile 4 could experience an increase of approximately 576 kWh over a year (40 kWh EV battery) and for Quintile 5 (60 kWh EV battery) is approximately 864 kWh over a year.

For Quintile 4, charging at 6pm (peak demand time) is the most expensive. The best TOU charging time would be at 8pm; additional costs when charging at 8 pm versus charging at 10 pm is very small. Based on the results for Quintile 5, the cheapest charging time is at 10pm.

There is a clear incentive to move charging away from peak tariff periods to off-peak, however, it is likely that there will be households where tariffs as a load shifting tool, may not be effective. These are the households where disposable income does not present restrictions because their investments and income are significant.

In terms of system dynamic modelling, by using an array of charging switches with random initial starting days and a variety of days between triggering, a close representation of a real population of electric vehicles could be obtained. When the driving feedback loop was added, the use patterns of different users and vehicles provided the same representative behaviour of the system as a whole. Following this approach allowed for a closer approximation of reality, which is critical to electricity suppliers who are both interested in the energy used to charge batteries, as well as the peak demand required.

RECOMMENDATIONS

It is recommended that the research be expanded to include an EV tariff to determine if that would provide a better incentive for EV owners to move off peak demand times.
It is also recommended that solar PV be simulated so that during loadshedding events, to determine the capacity required to power basic appliances and adequate power to charge the EVs.

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