Department of Mechanical and Aerospace Engineering

The Development of an Electric Vehicle and Charging Strategy Modelling Program

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Abstract

This project was carried out to investigate the potential impact that electric vehicles could have upon the grid within the near future as their numbers grow in response to improvements in battery technologies. Background research was initially carried out to gain an effective understanding of electric vehicles, their operation and how they would interact with the power grid.

Matlab was then used to develop a model that would simulate a prediction of what loads would result from increasing numbers of electric vehicles. Several scenarios were ran under different assumptions to estimate realistic results. Charging strategies were then developed and implemented to mitigate any significant loading that would occur during peak hours of residential demand.

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Nomenclature

EV – Electric Vehicle

HEV – Hybrid Electric Vehicle

BEV – Battery Electric Vehicle

PHEV – Plug-in Hybrid Electric Vehicle

EPA – Environmental Protection Agency

DNO – Distribution Network Operator

SOC – State of Charge

kW – Kilowatt

kWh – Kilowatt Hours

1. Introduction

With growing concern for the impacts that anthropogenic induced climate change could have upon the world, there are greater trends towards decarbonising required energy. Within the UK, the transportation sector required the largest demand of total energy in 2016 with a share of 40% at 55,767 ktoe [1]. Thus, a key step to reducing the potential impacts of climate change will be to produce an environmentally friendly transportation sector. Currently, one of the most promising methods to carry this out will be for greater development, and the inclusion of, the Electric Vehicle (EV). Large corporations have recognised this and are carrying out research into producing cost effective EVs to sell [2]. These Companies have been incentivised by governements through such decisions as to ban the sale of petrol or deisel vehicles in the UK by 2040 [3].

Due to this research and development, improvements in battery technology have been accelerated with more efficient and cost-effective manufacturing being undertaken [4].

To encourage the public to purchase EVs, charging stations have been created within cities that often provide free electricity to charge your vehicle [5]. In Glasgow alone, to date, there are over 80 public charging stations available for people to use [6] and more than 4,500 overall in the UK [7]. As private EV ownership increases, it is expected that household charging points will become the norm; however, as EV numbers increase, there is the potential for them to have a significant negative impact upon the grid due to increased loading on the distribution network [8]. This issue has the potential to be solved through implementing charging strategies and smart controllers, which may even result in the EVs providing a benefit to the grid, by such means as vehicle-to-grid generation, and even using the EVs as an on-demand load [9].

This project will develop a program that will simulate the application of EVs an estimate the impacts that their inclusion could have. A number of scenarios of EV application will be carried out and methods of impact mitigation, such as charging strategies, will be applied to demonstrate methods to solve the potential issues that EVs could present today's power grid.

2. Project Objectives

To carry out this project, several key objectives were set out and are as shown below.

- Carry out an extensive literature review
- Develop a basic EV charging model with uncoordinated charging
- Improve the uncoordinated model for more realistic charging methods
- Investigate and apply charging strategies to the EV model
- Investigate the potential for vehicle-to-grid generation
- Propose future work that would benefit current EV research

3. Literature Review

3.1 Development of Electric Vehicles

Whilst electric vehicles have been in existance since the 1800s, it was not until the early 21st century that they truly began to become significant [10]. This transition to EVs largely began due to the initial manufacturing of effective hybrid vehicles that operate using both batteries and combustion engines [10]. Today, there are three main forms of electric vehicles: Hybrid Electric Vehicles (HEV), which run using both petrol and electricity which is generated from regenerative braking systems; Plug-in Hybrid Electric Vehicles (PHEV), which also use petrol and batteries but are capable of charging by "plugging in"; and finally, Battery Electric Vehicles (BEV), which operate purely on a motor driven battery system [11]. Whilst BEVs produce no emissions themselves, their range is substantially less than that of hybrid vehicles and even more so than conventional vehicles. Despite hybrid vehicles providing a "best of both" approach to the reduction of emissions and effective driving range, they, alongside conventional vehicles, will be banned from sale in 2040 [3]. Thus, this project will concentrate purely on BEVs to provide a more realistic insight into the future transportation sector. It should be noted that when referring to "EVs" these will be battery electric vehicles unless specified otherwise.

In contrast to the lack of range available within an EV, it was found that the required fuel to travel a certain distance could cost the EV half of what would be expected when using a conventional gasoline fueled vehicle [12] , as shown in Figure 1.

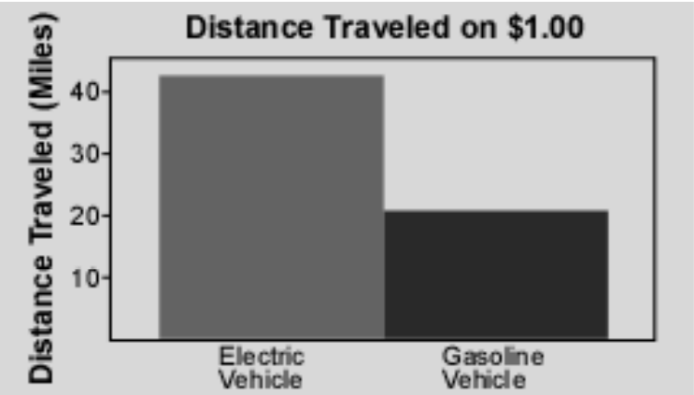


Figure 1: Distance on Different Fuels [12]

3.2 Electric Vehicle Usage

Today, in the UK, 77% of households have at least one car, with 34% of that total owning multiple cars [13]. Whilst vehicle ownership has been increasing, it is true to say that the total mileage each year has decreased in the past decade, however, not significantly enough to compensate for the increasing number of vehicles on the road [13].

As of August 2017, there were a total of 108,000 registered electric vehicles within the UK [14]. This number may seem quite large, although, in comparison to the number of vehicles registered in 2016 alone, this was merely 3.27% of the 3.3 million vehicles, and is almost insignificant when compared to the total number of licensed vehicles in the UK [15]. However, despite this being insignificant relative to the total number of vehicles, if countries are expecting to achieve the goals set out in the COP 21 summit, it is estimated that there will be a requirement of 140 million electric vehicles globally [16].

3.3 Electric Vehicle Performance

There has long been a general public scepticism when it comes to electric vehicles due to their relatively short range and high cost. The Nissan LEAF was the first mass produced electric vehicle with a battery capacity of 24 kWh and an estimated range of 84 miles (EPA) [17]. Whilst this vehicle was designed mainly for city use, it is evident that in comparison to conventional vehicles its performance is far from comparable. However, since the release of the LEAF in 2011, there have been numerous developments and improvements when it comes to an EV's performance.

Towards the end of 2016, the Tesla Model S was the world's best-selling electric vehicle, selling over 50,000 models [18]. The basic Model S contains Lithium-Ion batteries with a capacity of 75 kWh, capable of a range of around 200 miles (EPA) [19]. However, the starting price for a new Model S is £56,400, and so compared to fossil fuel based vehicles it is significantly more expensive for, still, a less than average range. Committed to developing a cost-effective solution for electric vehicles, Tesla will be releasing their Model 3 design, of which the basic model will contain their new 2170 lithium-ion battery cells with a starting capacity of 50 kWh; these new vehicles have been estimated to be capable of ranges over 200 miles [20]. With a starting price of £34,000 this vehicle promises to provide a significantly improved performance and fuel efficiency due to design improvements and reduction in friction losses at a drastically reduced price [20].

It is clear, that despite their improvement within the past decade, electric vehicles have a long way to go to surpass the conventional vehicle in its overall performance. Although, with more

and more large businesses committing to battery electric vehicles, their development and improvement will no doubt be accelerated, especially with Tesla leading the way with their production of the Gigafactory to mass manufacture lithium-ion batteries to be used in multiple products. The competition that will be incited from the interaction of large companies will no doubt benefit the end user as their products become improved over time, and thus, will drive the global economy towards accepting EVs as the norm, reducing the potential future impact that vehicles could have upon the environment.

3.4 Lithium-Ion Batteries

Lithium-ion batteries are currently the most widely used energy storage product. They are constructed simply with an anode, cathode and electrolyte to carry out a chemical reaction. Typically, the electrolyte can consist of a combination of lithium salts in an organic solution; lithium cobalt oxide is frequently used for the cathode and graphite for the anode [21]. A configuration of a cylindrical lithium-ion battery can be seen in Figure 2 [21] below and the typical compositions in Figure 3 [22].

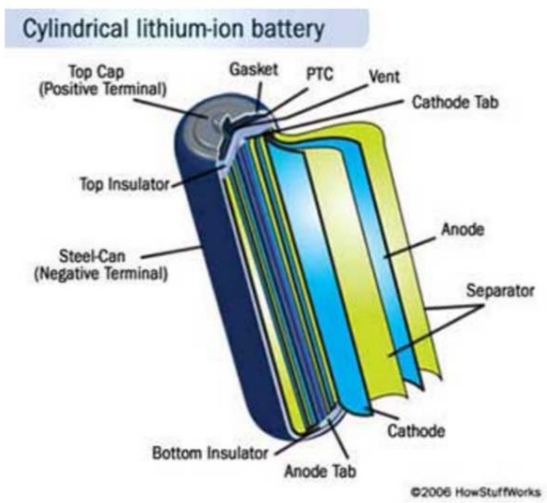


Figure 2: Construction of Li-ion batteries [21]

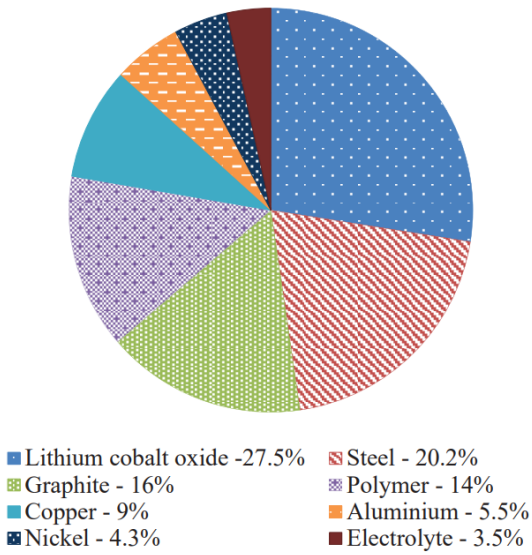


Figure 3: Composition of Li-ion Batteries [22]

Within the battery, the lithium-ion is the cation- a positively charged particle that travels from the anode to the cathode [21]. The reaction that takes place within the battery is a reduction-oxidation reaction (redox). This is where electrons are transferred from the anode, once a conductor is attached to the outlets, and then react with the available cations at the anode. A schematic for the reaction can be seen in Figure 4. Lithium-ion batteries are capable of recharging through carrying out the reaction in reverse using an input power source. One of the

significant benefits of these batteries is their capability to be recharged, or “cycled”, a high number of times without significant degradation occurring [21].

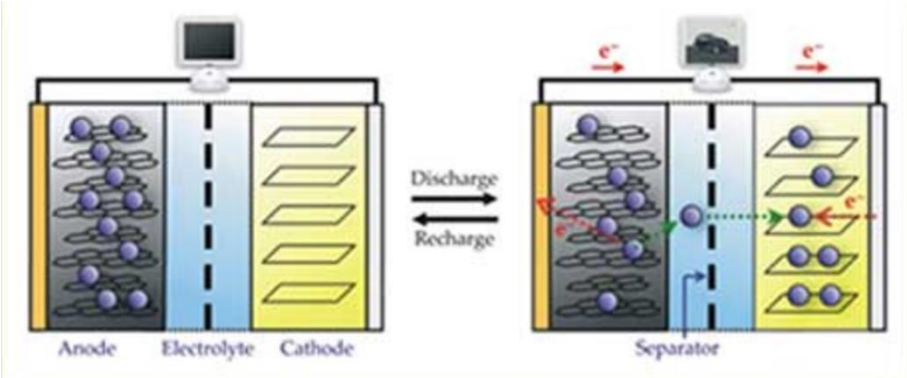


Figure 4: Li-ion battery chemical reaction [21]

Lithium-ion batteries are so widely applied and successful due to their excellent energy and power density in comparison to other battery technologies [23]. Alongside these excellent power qualities, lithium-ion batteries are also an extremely safe technology with one of the “safest battery chemistries available” [24]. Despite all these wonderful sounding properties, lithium-ion batteries still face some barriers to large scale application; these mostly being their current high costs and potential environmental impact [25].

Due to the high demand of lithium, to manufacture these batteries, the metal’s price has soared within the recent decade and quadrupled in price to nearly $8000 per tonne [26]. Whilst this will have significantly impacted the overall cost of the batteries, it should be noted that this is not the most expensive aspect of the batteries; the expense is normally found in the processing, and in cobalt that is required for the batteries [23]. Despite this increase in lithium cost, battery manufactures have managed to reduce battery costs from $1000/kWh to a claimed $190/kWh [25]. Tesla have been one of the main drivers for reducing the cost of these batteries and are claiming that they will be able to achieve the cost goal of $100/kWh by 2020, whilst other companies estimate this will be achieved by 2030 [25]. This cost goal is a target set to achieve a cost-effective lithium battery design that can be widely distributed in EVs to the public at a cheaper cost. If the target is only achieved by 2030, despite Tesla’s claims, then this will still provide a 10-year transition period until the UK’s banning of the sale of fossil fuel vehicles.

Tesla is a frontrunner in the lithium-ion battery manufacturing and is accelerating their capabilities through the construction of their Gigafactory. Pairing up with Panasonic, they have recently started mass producing their newest battery, the “2170” and aim to be producing 35

GWh of batteries annually by 2018, which is more than all of the world's current battery production combined [27].

Whilst battery prices are predicted to keep dropping ,and become more cost-effective, there are concerns for the impact that the use of lithium could have on the environment and its availability as a source. Lithium is largely extracted from salt marshes in Argentina and Bolivia- Figure 5 shows a section of land where this extraction is occurring [28]. Obtaining lithium clearly has a significant visual impact upon the surrounding environment, and the calcification process of obtaining the lithium also produces up to 12.5kg of carbon dioxide per kg of lithium that is produced [29]. However, with the lithium being primarily used as a form of energy storage which will enable the reduction in the use of fossil fuels, it is evident that this is an environmental cost that will no doubt be paid off through the use of renewable energies.

Figure 5: Lithium extraction site [28]

Concerns have also been raised for the availability of lithium as a metal, but these have been rebuked after research has proposed that there is enough lithium within the crust of the earth alone to create a "global fleet" of electric vehicles [21]. To further this argument, the speculation that oil will run out within a few decades has been made for over 50 years, but as technology has improved more oil has been able to be harnessed- this will most likely be true with lithium as well. Not only this, but current methods of recycling lithium-ion batteries are capable of recovering over 50% of the natural materials after usage, and so this will no doubt

play a large part in the manufacturing of new batteries as battery usage is expected to at least double within the next decade [22].

Currently, lithium-ion batteries are the most effective form of energy storage. Their cost is being driven down through research and improvements in manufacturing processes, and they will most likely become a far more cost-effective method within the coming decade. However, as further research is being carried out into other forms of energy storage, there could be developments in future technologies that are capable of out-performing the standard lithium-ion batteries.

3.5 Electric Vehicle Charging

As electric vehicles are limited to the range provided by the capacity of their batteries, effective charging systems is a significant factor to enable users to keep their vehicles at an appropriate level of charge. There are a number of methods for charging an EV, each with its own benefits.

3.5.1 Plug-in Charging

The first method for charging is the most obvious, to simply plug in the vehicle to an electrical outlet similarly to every other common electrical product. However, as EVs require such large amounts of energy to be stored, there has been a development of multiple levels of chargers, details of which can be seen in Table 1 [30]. The “Power Nominations”, shown in the first column, can also be known as “Trickle Charging”, “Moderate Charging” and “Fast Charging”. These different levels of charging are capable of providing power at different rates, with hHigh power charging being capable of providing a full charge within half an hour for most electric vehicles [31]. Although, even though this is an extremely fast rate of charging, it is still a relatively long time when comparing it to refuelling a conventional vehicle. When fast charging, to maintain the battery’s lifetime, the battery should not be fast charged over 80% of its capacity but instead should receive a lower power input after this point [32].

Table 1: Charging levels of electric vehicles [30]

Power nomination	Mains connection	Power in kW	Power in Amps	Recharge range/hour[3]
Normal power[4]	1-Phase AC connection	≤ 3.7kW	10-16 amps	<20 km
Medium power	1- or 3-phase AC connection	3.7 -22 kW	16-32 amps	20 – 110 km
High power	3-phase AC connection	> 22 kW	> 32 amps	>110 km
High power	DC connection	> 22 kW	> 32 amps[5]	>110 km

To encourage people to purchase new electric vehicles, councils have been installing public charging points throughout their cities. Glasgow itself has installed over 80 which provide a high-power outlet of 22kW [6]. However, for private vehicle owners it will be most likely be necessary to have their own private charging stations at home which will incur an extra cost for the initial purchasing of the vehicle. The household charging systems will probably have a combination of chargers in order to meet the needs of charging time that the owners require.

3.5.2 Batter Swapping

Another method of charging a vehicle's battery is to have a spare battery that is charged whilst one is being used within the vehicle, this battery can then be directly swapped when the charge runs out, providing an instantaneous replenishment of energy as displayed in Figure 6 [33]. This method has obvious barriers of cost and complexity that are not included when a standard plug-in charging method is used. It is for this reason that this method would no doubt be unsuitable for private users, but instead, companies could provide a contractual swapping service as discussed in [34]. Using such a system will enable the batteries to be recharged during off-peak hours thus reducing potential impacts upon the grid [34]. However, due to the numerous battery designs that are used currently and with newer designs to be released relatively frequently, this system will have complexities in matching the correct battery demand unless a universal style is adopted.

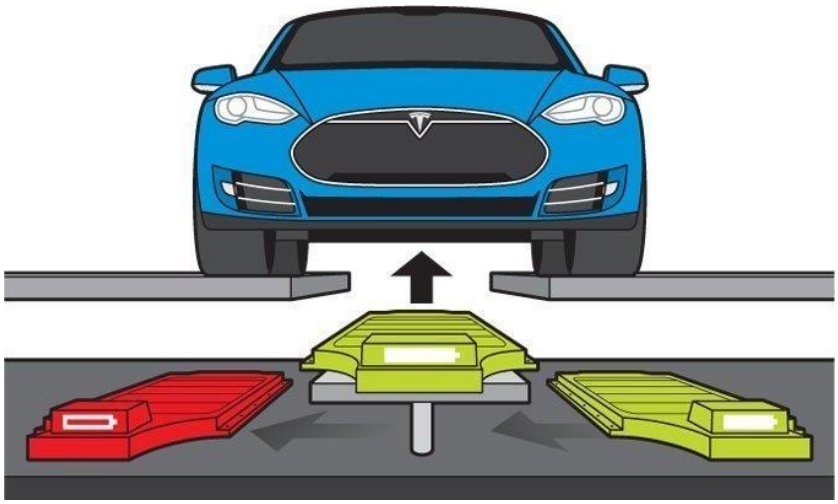


Figure 6: Battery swapping diagram [33]

3.5.3 Inductive Charging

Inductive charging, or wireless charging, is another potential form of battery charging that could be applied. This takes advantage of the magnetic field created through coiling a wire a specified number of times which is then capable of transferring the current to an adjacent conductor- a simple circuit for this process can be seen in Figure 7 [35]. This would provide the most simplistic method of charging an EV as the user would literally just have to park in an allocated spot and automatic charging would occur. There have even been proposals to integrate wireless chargers within road surfaces for constant charging whilst driving [35]. However, using wireless transmission introduces extra losses and is found to reduce the efficiency to around 80% [36].

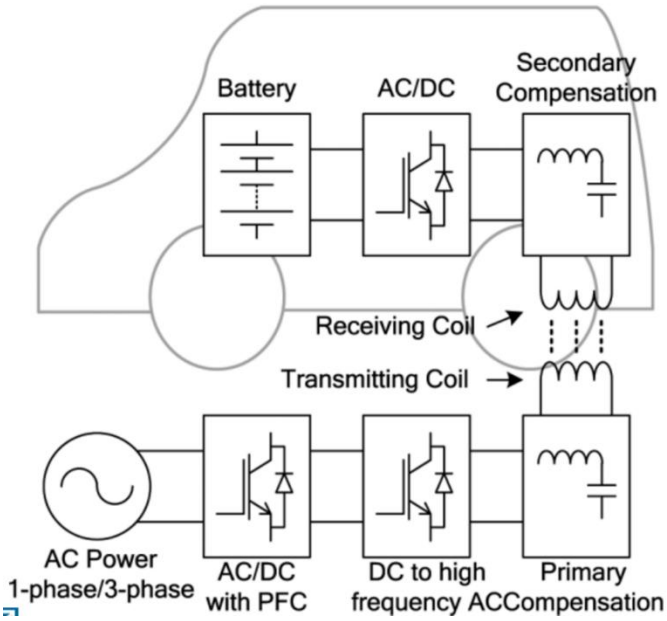


Figure 7: Induction charging schematic [35]

Whilst wireless transmission is an extremely attractive method of charging, this reduced efficiency is quite significant and would greatly impact the total load applied to grids, as well as increase the cost to the user. It is most likely for one of these reasons that the EV manufacturer Tesla cancelled its wireless charging project.

3.6 Potential Impacts of Electric Vehicles

As the number of electric vehicles increases, they will most likely put greater strain upon the distribution grid and affect several areas for future grid plans. Uncoordinated charging could lead to increases in power demand during current peak demands, and thus potentially have significant impacts upon the current distribution grids that are not rated for such a high demand [37] [38] [39]. Figure 8 [38] displays a possible increase in daily demand due to the incorporation of EVs.

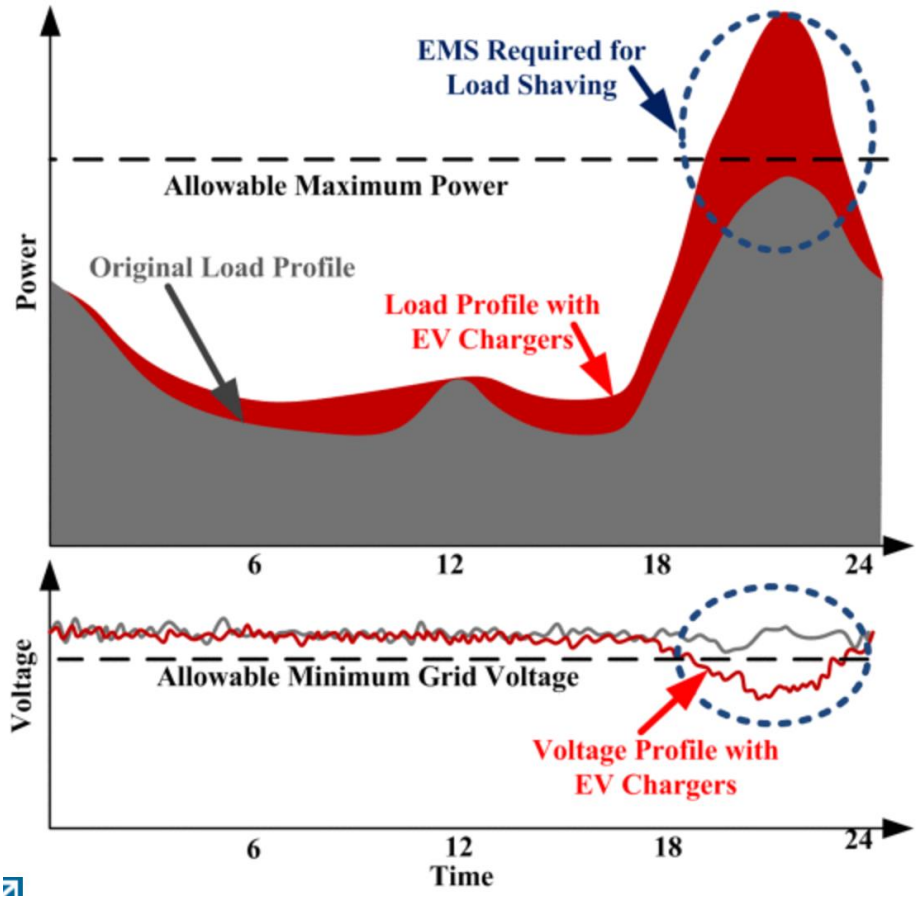


Figure 8: Potential EV Impact upon load curve [38]

3.6.1 Impact on Power Quality

The inclusion of EVs within the current grid may impact power quality in several ways if a completely uncoordinated approach to charging is used by the public. Most notably of these are: a significant increase in the production of harmonics within the grid, unacceptable voltage drops, and three phase imbalances [37].

The amount of harmonics within the system will be increased substantially alongside the number of electric vehicles, due to the required implementation of extra charging equipment. These chargers will incorporate further power electronic devices which can produce harmful levels of harmonics, especially if applied on a large scale [37].

Figure 9 shows the potential impact EVs can have on the voltage profile throughout the day. If an uncoordinated approach is taken to towards charging the EVs then increased loading during peak hours will cause extra voltage drops, which may exceed the 10% voltage drop limit set by the EN50160 standard. If this occurs, it will be possible for some electronic devices to become damaged or operate incorrectly due to this fluctuation in voltage [37].

With EVs being a largely unpredictable load, without preventative measures in place, they may also cause three-phase current balance within the system [37].

3.6.2 Network Planning

Network planning will have to consider the future demand from electric vehicles otherwise further impacts could be experienced. Locations that are planned to have large charging facilities will require a reinforced transmission infrastructure, otherwise it will impact the power quality, increase costs and hinder EV users within the area [37].

3.6.3 Operational Impacts

Throughout the operation of the distribution system, EVs can have effects not only upon power quality but also in such areas as increasing losses and damaging valuable equipment. Power losses will increase with greater penetration of EVs, especially considering that fast chargers will incorporate higher Ampage to decrease the time of charging [38, 39]. With power fluctuations occurring, cables will undergo greater levels of stress which will reduce their lifetime and operational performance. Transformers are relatively sensitive to fluctuations and so will also be susceptible to such power quality reductions [37]. All of these issues will infer greater operational and maintenance costs from the inclusion of electric vehicles.

It is clear that electric vehicles, if not managed appropriately, have the potential to cause some serious damage to the current grid networks. However, if they are managed correctly, there may be opportunities to be taken advantage of.

3.7 Mitigation and Opportunities

Methods of mitigation can be applied to electric vehicles in order to minimise the effect that they have upon the grid; this could come in the form of contractual charging methods, charging incentives or even through smart grid systems [8, 37]. Incorporating any of these mitigation methods will likely result in positive outcomes for the Distribution Network Operators (DNO) through reducing overall impact on the grid and potentially even reducing the total cost for upgrading the system.

From the perspective of grid operators, EVs can be viewed as an intermittent load or even a generator if vehicle-to-grid transmission is possible. This provides the opportunity for grid operators to set up tariffs with EV users for them to be able to act as a load or generator during certain hours, similarly to current dispatchable and ancillary services that are used. Taking advantage of these aspects would enable electric vehicles to help flatten out daily load profiles preventing too great a change from peaks and troughs. This idea is represented in Figure 9 below [40].

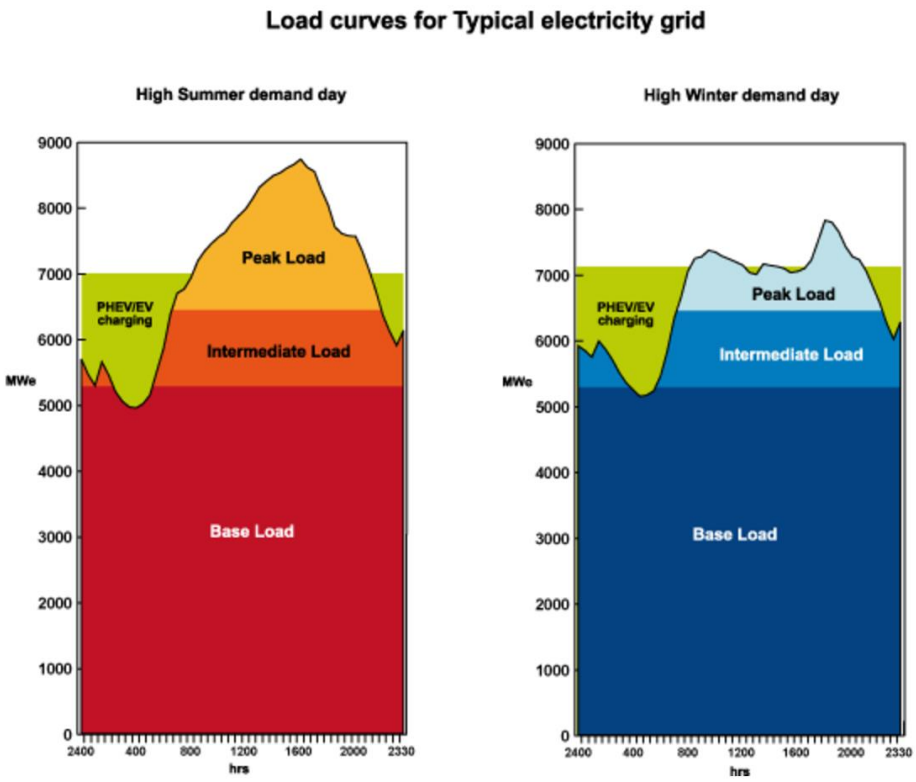


Figure 9: Potential benefit of charging strategies [40]

Implementing such a strategy would provide numerous benefits to not only the grid operator but also the EV owner. The EV owners would be able to receive tariffs for any time that their vehicles are used without carrying out any operation. The grid operators would be able to not only reduce losses and provide a more reliable power source, but could take further advantage of baseload generators instead of requiring the operation of contractual dispatchable generators whenever the grid requires it. These baseload generators provide reliable power at a far cheaper cost in comparison to such dispatchable sources as gas turbines or diesel generators.
Another benefit will be increased utilisation of distributed energy sources at their location. With the stochastic nature of wind farms and the semi-unpredictable nature of solar arrays, large scale energy storage has long been sought after to counteract over-generation to prevent unnecessary expenditure to deactivate any wind turbines. EVs could provide the very solution to this issue with wind farms being used to charge electric vehicles when they would have otherwise been generating unnecessary energy.

After carrying out the above research, it is evident that applying effective charging strategies has the potential to provide numerous benefits to the operation of the grid, and could even lead to a decrease in the average cost of electricity for the end user. Whilst there are concerns for large scale application of EVs, through carrying out analysis and research it may possible to develop a more reliable power grid that takes greater advantage of renewable resources and leads the way to a future of clean energy.

4. Project Justification

After carrying out extensive background research into electric vehicles and their potential effects, without implementing substantial management or mitigation measures, they could greatly impact the power grid and customers. With the potential for such significant impacts as increased loading at network nodes- that could cause component failure, reduction in power quality, and increased losses across the network- it is evident that research must be carried out in order to have a smooth transition to the extensive use of EVs.

Effective predictive models for EV usage will be necessary to ensure this, and should be used to demonstrate the impact that large scale EV vehicle application could have, charging strategies that could be applied and also potential benefits that could be gained from effective EV management.

Numerous studies have been carried out on cases of electric vehicle application and their impacts, however, these investigations develop models and results for only a specific scenario with limited variables. This project aims to develop a model that can be used to simulate the application of any number of EVs with varying vehicle models and capabilities. This should provide a more realistic simulation of EV application and the ground work for future, further developed, models.

5. Methodology

To develop an effective EV modelling program, initially, a basic program was created and then complexities were added for more realistic outputs. The project followed a development methodology where the program would be coded, validated, and then improved. This cycle occurred a number of times until the basic program contained more complex boundary conditions that should provide effective EV simulations. Reliable data was initially sourced to provide the required inputs into the program.

5.1 Sourced Data

The program was created to be capable of simulating not only one type of EV but also a fleet of EVs with varying characteristics and charging requirements. To fulfil this the following data was used to generate vehicle behaviour and characteristics depending upon probabilities.

Vehicle Characteristics

Three vehicles were selected based upon their differing characteristics, capabilities and price. These vehicles were chosen to be the Nissan Leaf, the Tesla Model S and the Tesla Model 3. The Nissan Leaf is a city vehicle with a small battery capacity of 30 kWh and is said to have a range of up to 155 miles [41], the Model 3 is Tesla's response to the need for an affordable effective EV with a battery capacity of 60 kWh and an ideal range of 220 miles [42], and the Model S is a luxury family vehicle with top of the range vehicle characteristics, with a battery capacity of 85 kWh and an ideal range estimation of 250 miles [43]. The vehicles are selected within the program by assigned probability factor which allocates them each with one-third of a chance of occurring. The stated ranges are under ideal circumstances and realistic ranges are dependent upon driving behaviour and average speed, to compensate for these uncertainty factors, ranges were estimated and assigned dependent upon the vehicles and probability factors, these vehicle characteristics can be seen in Table 2.

Table 2: EV modelling characteristics

	Leaf			Model 3			Model S		
Battery Capacity (kWh)	30			60			85		
Ideal Range (Miles)	155			220			250		
Input Range (Miles)	100	120	140	120	140	175	175	200	225

Vehicle Chargers

As discussed before, there are a number of methods for charging EVs, however, the most simplistic is standard charging via a cable and so this project will only concern itself with this method. Within plug-in charging, there are also various levels at which the vehicles can be charged dependent upon the input power. The selected levels for charging the vehicles at are listed below in Table 3, 3.7 kW is "trickle charging", 11 kW is the equivalent of Tesla's home charger [44], the 22 kW is the same output that will be provided by public charging stations throughout Glasgow [6] and the 145 kW is the Tesla Supercharger [45]. However, for the initial basic program it was assumed that only 11 kW chargers would be used.

Vehicle Trip Probabilities

One of the most unpredictable factors within the program will be effectively predicting the behavioural aspects of EV users. This includes the prediction of when trips will occur throughout the day. To generate relatively realistic behaviour, data was taken from the UK National Travel Survey which estimates the probability of trips occurring throughout the course of the day [46]. The probabilities were extracted similarly to the work carried out in [47] and these are shown in Figure 10. This project will only use the probabilities for weekdays as these should provide the worst case scenario for EV charging.

Table 3: Levels of charging for EVs

Level 1	Level 2	Level 3	Level 4
3.7 kW	11 kW	22 kW	145 kW

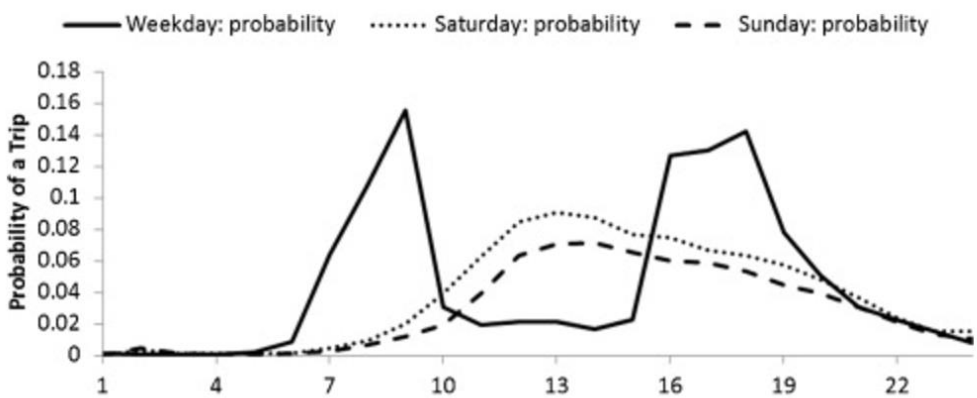


Figure 10: Trip probabilities over 24 hour period [47]

Vehicle Trip Distances

Similarly to estimating the occurrence of a trip, estimating the length of a trip is again difficult due to the human behaviour involved. The data that was selected to generate the trip lengths was taken from [48]. This paper investigated car journey behaviour on a large scale, the most appropriate selection of data was for that of Germany as this would be the most suitable behavioural pattern in comparison to the UK travel data taken for the probabilities. This paper thus resulted in an average trip journey of 65km being used per iteration.

5.2 Basic Program

The basic program used this selected data to carry out analysis on the impact due to individual vehicles as well as large quantities of vehicles over a set period of time. The program dictates individual vehicles behaviour through assigning states for each iteration of the code, these states determine the action that is performed by the vehicle and are illustrated in Table 4. A number of scenarios were then simulated to investigate the loads generated due to EV application. However, assumptions and estimations had to be made in order to carry these out.

Table 4: Assigned EV states

State 1	State 2	State 3	State 4
Vehicle begins a trip based on distance factor	Vehicle is still on trip but no further energy consumption	Vehicle charges dependent upon input power	Vehicle is idle

Assumptions and Estimations

With EV usage being derived purely from human behaviour, inaccuracies are inevitable and so it should be noted that there are multiple assumptions that, whilst necessary, are likely to decrease the accuracy of the results. This can first be found in the selection of a vehicle, when selecting a vehicle, it is assumed that the vehicle is capable of being 100% charged and utilising all of this available energy. Not only this, but also that the battery can be recharged perfectly without any degradation occurring to the battery over time.

It also assumed that the vehicle will be able to travel for a fixed range on the assigned battery capacity, as discussed earlier, the range of a vehicle cannot accurately be depicted and so would realistically be changing constantly. From the vehicles that are selected, there are only three differing models, albeit with different assigned ranges, but this does not accurately represent the large variance of EVs in even todays markets.

To initialise the calculations, the State of Charge (SOC) of the battery was initially generated using a random probability between 20% and 80%. These results are shown in Figure 12 below, which depicts a simulation over a 48 hour period with 100 vehicles. It is immediately evident that applying such a range to the SOC offsets the results of the first few iterations substantially, and so the range was changed to 60%-80% to reduce this unrealistic peak in demand. This provided the results shown in Figure 13, whilst this did reduce the quantity of vehicles contributing to the peak in demand, there is still an unrealistic peak and this should be discounted during the analysis of the results.

The probability of a trip occurring and the length of this trip are estimated using the data sourced above, whilst this will provide more realistic results it will not directly mirror the loading produced in reality. A completely realistic model will only be achievable with dedicated data found for such a simulation.

The reduction in charge due to a trip and the energy gained during charging do not take into account a number of losses that would occur during each process. The SOC reduction is calculated using the estimated range of the vehicle and so is a serious estimation in the reduction of the SOC. The vehicle charging also assumes ideal energy transfer and does not take into account any electrical or electro-chemical losses that occur during real scenarios.

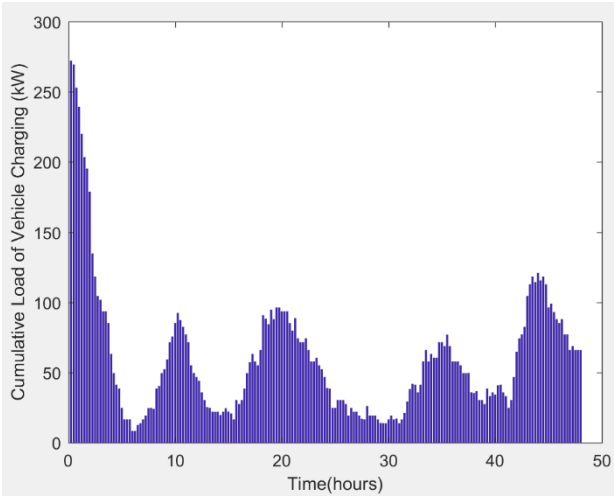


Figure 11: SOC Generated between 20%-80%

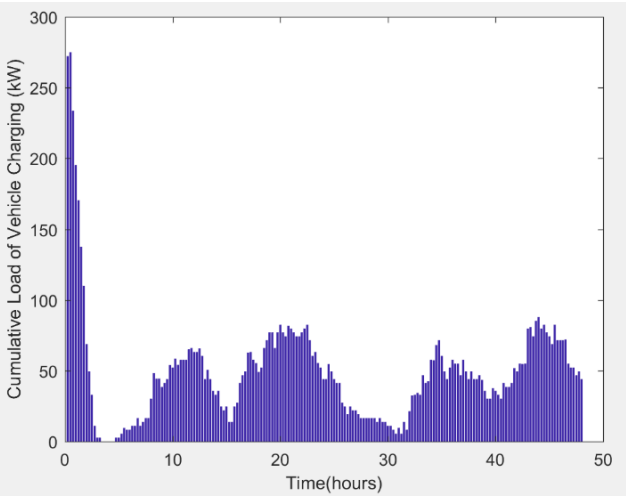
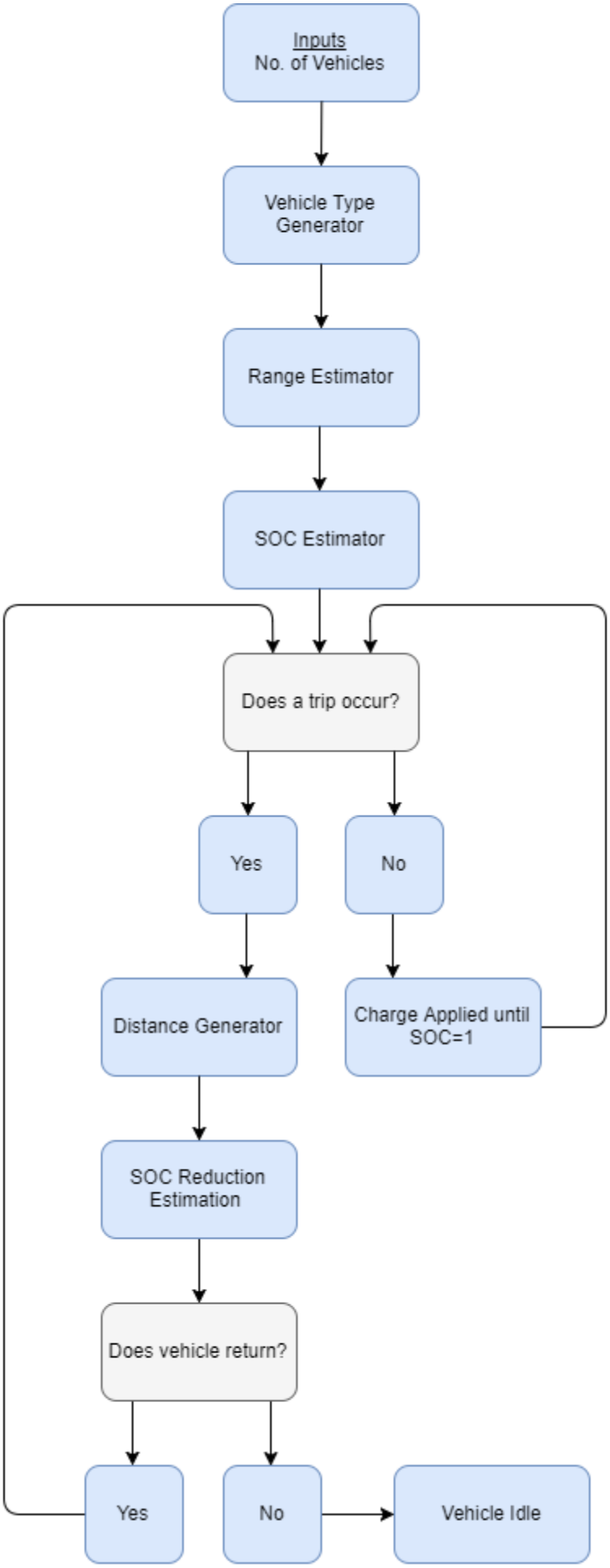


Figure 12: SOC Generated between 60%-80%

Basic Program Block Diagram



Basic Program Process Evaluation

The block diagram above displays the overall process under which the basic program carries out a simulation for each vehicle. Through each of these iterations the program calculates any change in charge that would occur due to the vehicles state and thus what required loading would be required over time for charging the battery when it returns home. For this simple program it was assumed that whenever the vehicle is at home and its charge is less than 100% then the vehicle would charge with the assigned 11kW input. This program, whilst not providing the most realistic results, enabled for estimation as to the loading of EVs over a 48 hour period. However, to be sure that the results, whilst an estimate are still relatively accurate, calculations were carried out to validate the programs capabilities.

Basic Program Validation

To validate the calculations made by the program, variables within the program were set to a fixed output in order to control the result of each function. Hand calculations were then carried out to ensure the validity of the program and that no extra human error factors were generated. Table 5 below shows the controlled variables with the calculated outcomes.

The first validation process carried out calculations for a single iteration of the program with a trip occurring, the results shown in Table 6 and the calculations below.

Table 5: 1st Validation Variables

Variables	Iteration
Vehicles	1
C	1
Capacity (kWh)	30
R	1
Range (Miles)	100
SOC	0.5
O	0.4
Trip Occurs?	Yes
d (distance)	30
X	0.1
Return from Trip?	Yes

Table 6: 1st Validation results

Results	Iteration
Available Range (miles)	20
Available Capacity (kWh)	6
SOC	0.2
Load (kW)	2.75
Vehicle State	2

$$Capacity = 30kWh, Range = 100\ miles, Soc = 0.5$$

$$Available\ Capacity = SOC\ x\ Capacity = 15\ kWh$$

$$Available\ Range = SOC\ x\ Range = 50\ miles$$

$$Trip\ occurs\ \therefore State = 2, d = 30\ miles$$

$$New\ Available\ Range = 50 - 30 = 20\ miles$$

$$SOC = \frac{20}{100} = 0.2$$

$$New\ Available\ Capacity = 0.2\ x\ 30 = 6kWh$$

Another validation was then carried out with different variables to ensure that the program still functioned correctly when the vehicle was charging and not on a trip. These results are shown below.

Table 7: 2nd Validation Variables

Variables	Iteration
Vehicles	1
C	0.1
Capacity (kWh)	85
R	0.1
Range (Miles)	225
SOC	0.5
O	0.7
Trip Occurs?	No
Applied Load (kW)	2.75

Table 8: 2nd Validation Results

Results	Iteration
Available Range (miles)	119.79
Available Capacity (kWh)	42.25
SOC	0.5324
Load (kW)	2.75
Vehicle State	3

$$Capacity = 85kWh, Range = 225\ miles, Soc = 0.5$$

$$Available\ Capacity = SOC\ x\ Capacity = 42.5\ kWh$$

$$Charging\ occurs\ \therefore State = 3, Applied\ Load = 2.75kW$$

$$New\ Available\ Capacity = Available\ Capacity + Applied\ Load\ = 42.5 + 2.75$$
$$= 45.25\ kWh$$

$$SOC = 45.25/85 = 0.5324$$

$$New\ Available\ Range = 0.5324\ x\ 225 = 119.78\ miles$$

Basic Program Scenarios

To demonstrate the loading that can be generated from EVs using the basic program, a number of scenarios were implemented. Table 6 displays the details of each scenario, the simulation was run over a 48 hour period with each iteration representing a 15 minute period. These scenarios were devised to display each of the vehicle types throughout this duration along with the cumulative effect of 10 and 100 vehicles when applied. Scenarios 2 and 4 can be found in Appendices X and X otherwise the results are shown below.

Table 9: Basic Program Scenarios

Scenarios	Charging Strategy
1. 30kWh Vehicle	None
2. 60kWh Vehicle	None
3. 85kWh Vehicle	None
4. 10 Vehicles	None
5. 100 Vehicles	None

30 kWh Vehicle

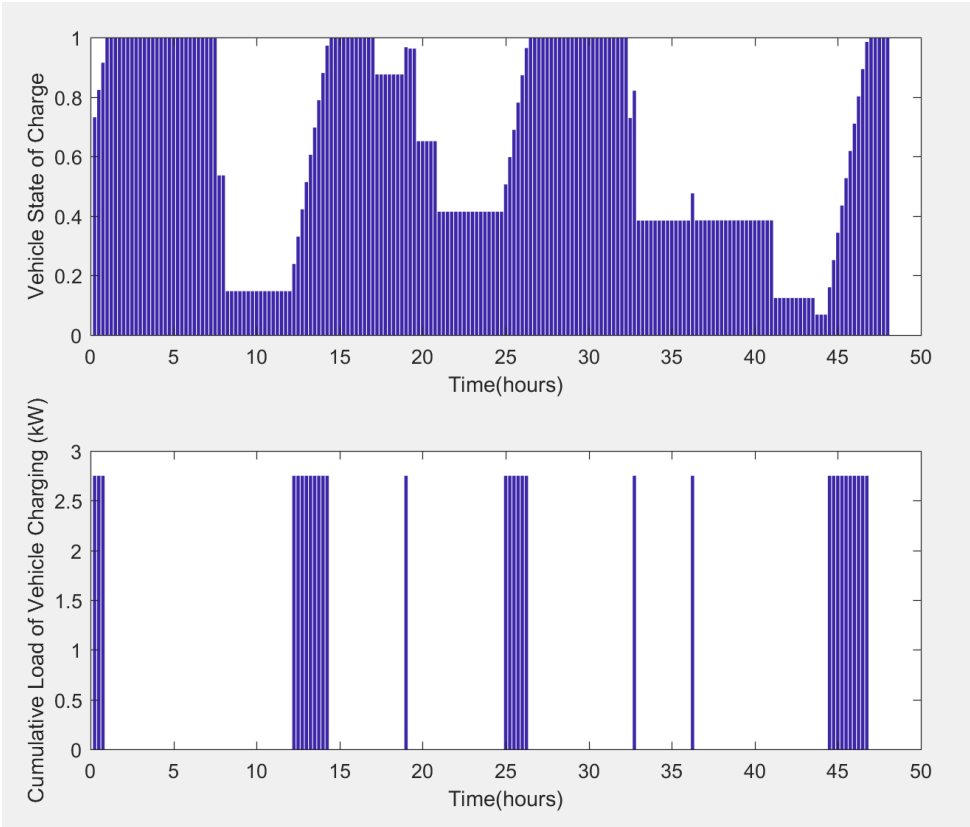


Figure 13: Loading results for 30 kWh vehicle

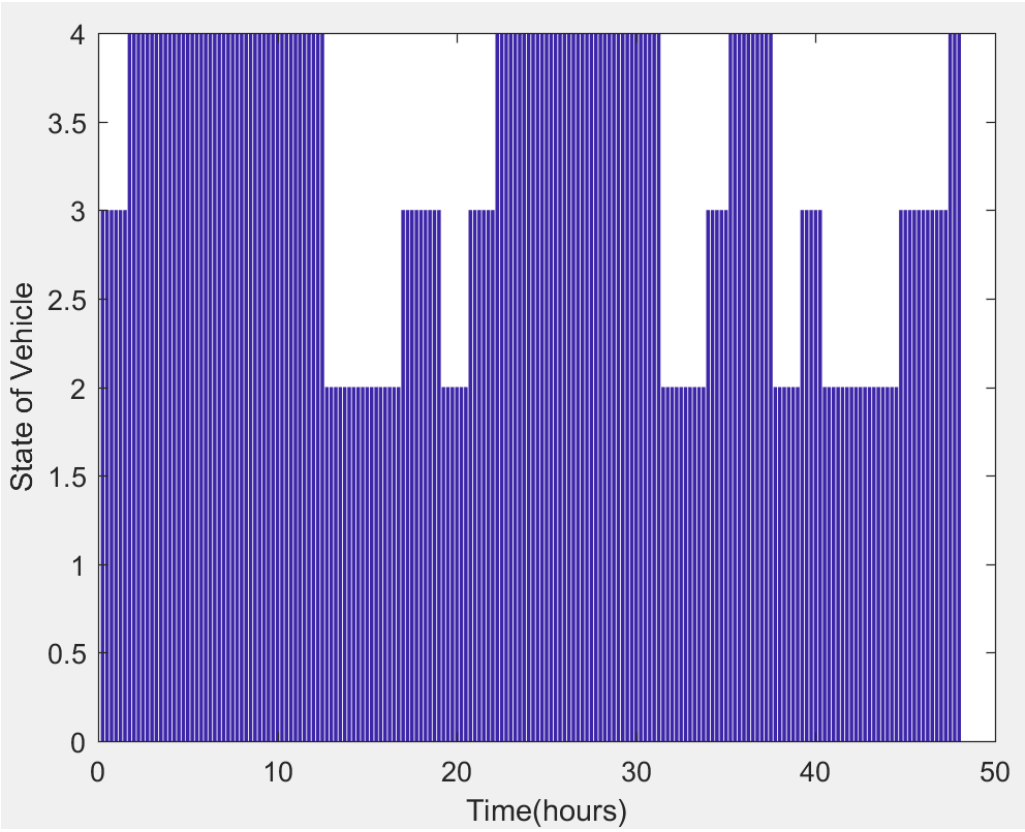


Figure 14: Results for 30 kWh vehicle states

85 kWh Vehicle

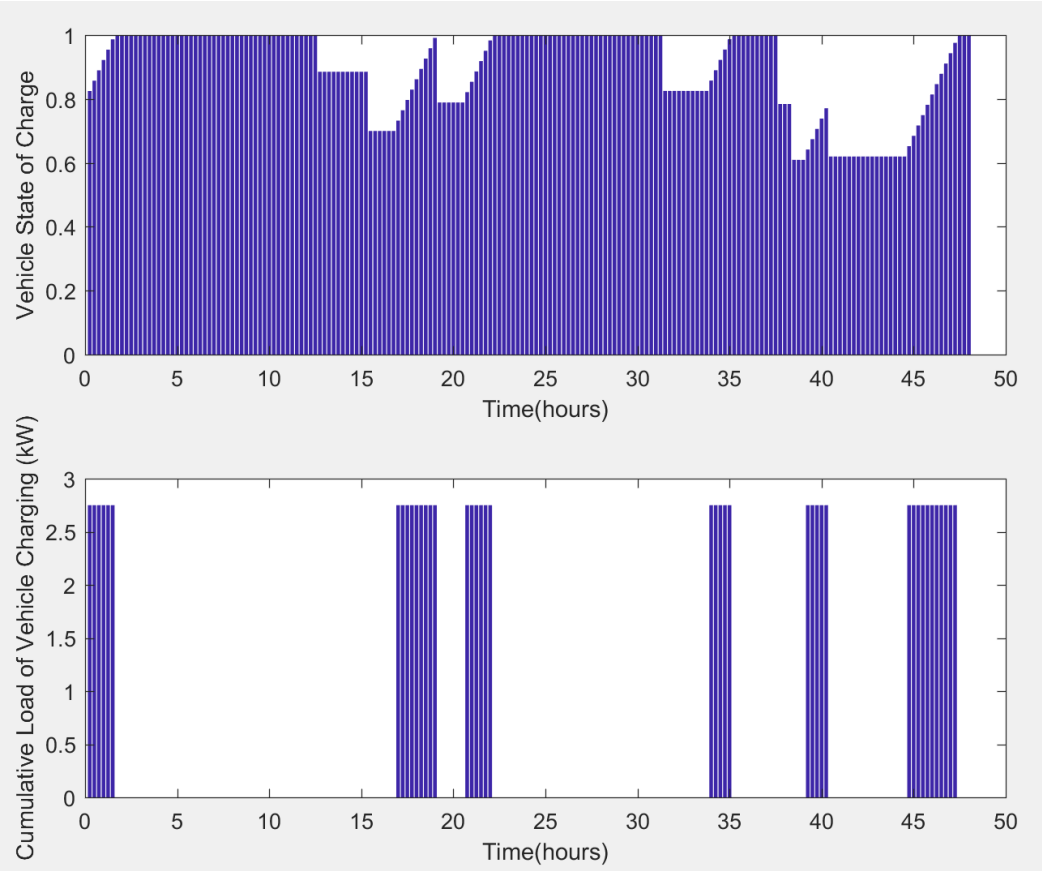


Figure 15: Loading results for 85 kWh Vehicle

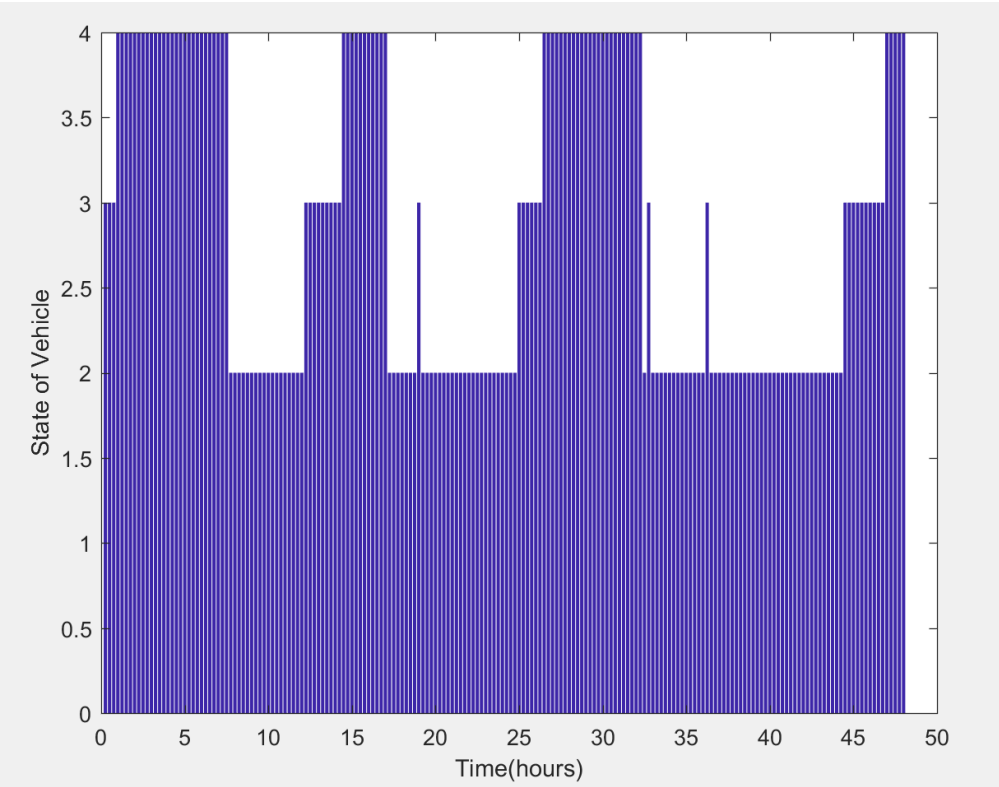


Figure 16: Vehicle state results for 85 kWh vehicle

100 vehicles

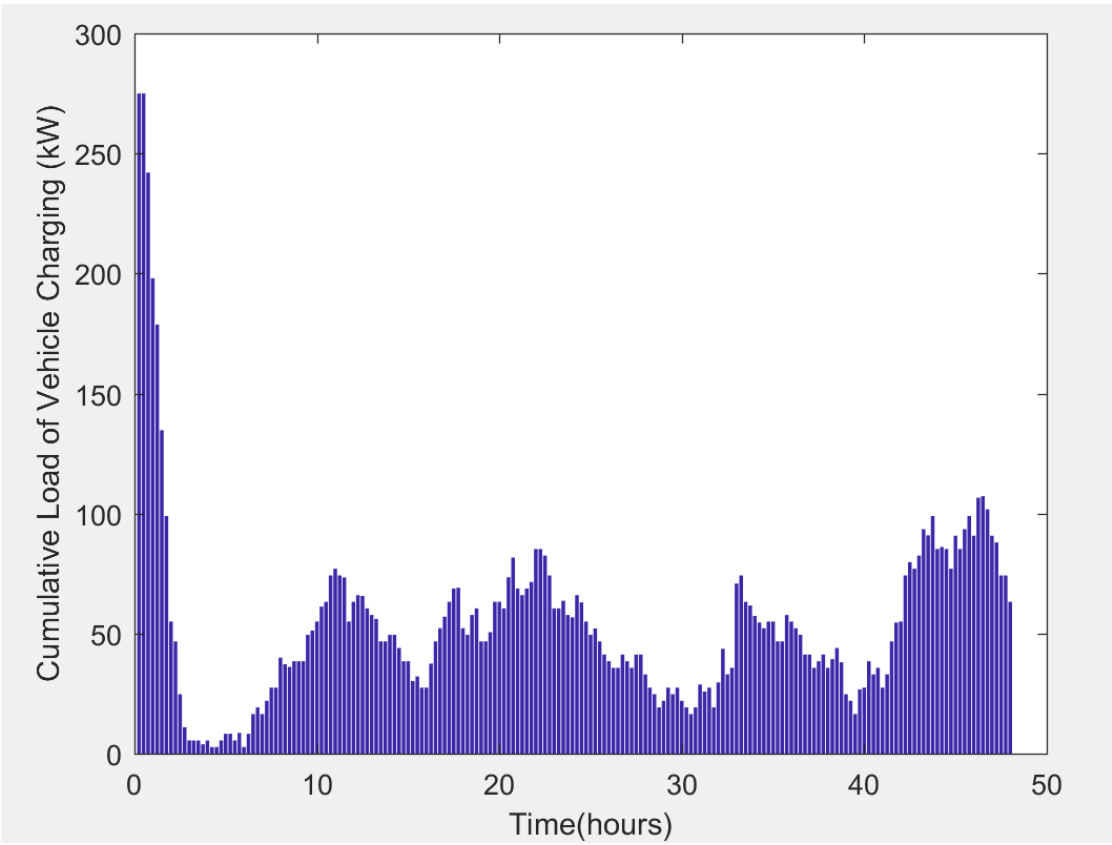


Figure 17: Cumulative Loading Results for 100 Vehicles

Basic Program Results

From the results shown from the analysis of each of the individual vehicles, it is evident that no matter the vehicle type, the load generated by the vehicle is largely due to the daily usage of the vehicle. Table 7 shows the cumulation of each of the vehicle's load generated over the 48 hours, these values change constantly due to the different distances generated by the algorithm.

Table 10: Loading results for basic program vehicles

Scenarios	Cumulative Load (kW)
1. 30kWh Vehicle	82.25
2. 60kWh Vehicle	96.25
3. 85kWh Vehicle	115.5

Analysing the two graphs of the cumulative loads for 10 and 100 vehicles the flaw in the generation of the SOC initially is evident. However, ignoring this peak, the graph displays expected daily loads for EV that charge on demand.

The loads generated throughout the day clearly display the issue that would occur if vehicle charging was left uncoordinated. Peaks in demand are shown to occur during current peak power demand hours, i.e. early evening (5PM-10PM). This displays the need for implementing some form of control over vehicle charging.

5.3 Improved Program

The basic program was then given several updates to provide a more comprehensive simulation of electric vehicles. These updates provided a number of functions for more realistic charging methods and even the capability to implement charging strategies for a pre-determined fraction of the vehicles.

Introduced Improvements

The first improvement that was implemented was the capability for the program to account for different levels of charging. It was assumed that vehicles would receive a minimum of 11kW of power input as their primary charging source. Each level of charging was given a probability of occurrence as shown in Table 8, this should provide more realistic charging results as even today there are varying designs in vehicle chargers. As shown in Table 11, it is expected that the majority would be 11kW followed by 22kW chargers with a small fraction using the 145kW chargers as these have not been implemented on a large scale in comparison.

Table 11: Probability of different charging levels

	Level 1	Level 2	Level 3	Level 4
Power (kW)	3.7	11	22	145
Probability of Occurrence	0%	50%	40%	10%

The second improvement was to further the realistic nature of the charging method, this implemented limits at which high power inputs would be used. Similar to other studies, the limit applied the 3.7kW power input when the vehicles SOC exceeded 80%. If applied in reality, this should enable for extended battery life due to reducing degradation of the battery cells.

The most significant alteration that was made was the introduction of charging strategy capabilities. This change will allow the program to dictate when charging occurs throughout the analysis and the number of vehicles that charge during this time period. This change should enable for effective charging strategies to be implemented to not only prevent increased peak loads but also flatten the over all domestic daily load profile.

The program should now be able to provide a more realistic simulation of on demand charging of EVs with both varying the types of EVs used as well as varying power sources for charging. The block diagram below demonstrates the improved process that the program carries out for these simulations.

Improved Program Validation

The program was then validated to ensure that the applied updates are carried out without any errors. The only necessary validation was one that validated the new charging methods and so this was carried out using the Level 4 charger rating to demonstrate the program functioning correctly. Comparing the calculations and the tables below it is evident that there are no errors within the code.

Table 12: 3rd Validation Variables

Variables	Iteration
Vehicles	1
C	0.1
Capacity (kWh)	85
R	0.1
Range (Miles)	225
L	0.99
Charger rating (kW)	145
SOC	0.5
O	1
Trip Occurs?	No
Load Applied (kW)	36.25

Table 13: 3rd Validation results

Results	Iteration
Available Range (miles)	208.46
Available Capacity (kWh)	78.75
SOC	0.9265
Vehicle State	3

$$Capacity = 85kWh, Range = 225\ miles, Soc = 0.5$$

$$Available\ Capacity = SOC\ x\ Capacity = 42.5\ kWh$$

$$Charger\ rating = 145\ kW$$

$$Charging\ occurs\ \therefore State = 3, Applied\ Load = 36.25kW$$

$$New\ Available\ Capacity = Available\ Capacity + Applied\ Load\ = 42.5 + 36.25$$

$$= 78.75\ kWh$$

$$SOC = 45.25/85 = 0.927$$

$$New\ Available\ Range = 0.927\ x\ 225 = 208.46\ miles$$

Investigated Scenarios

For the improved program, as the different vehicles had been investigated earlier, the newly introduced different levels of charging were simulated. The different scenarios are shown in Table 9 with each level of charging being applied to the 60 kWh vehicle with its range set at 175 miles. These results were simulated alongside new 10 and 100 vehicle simulations to review the impact that the changes have on the cumulative loading.

Table 14: Improved Program Scenarios

Scenarios	Charging Strategy
1. Level 2 Charging	None
2. Level 3 Charging	None
3. Level 4 Charging	None
4. 100 Vehicles	None
5. 1000 Vehicles	None

Level 2 Charging Results

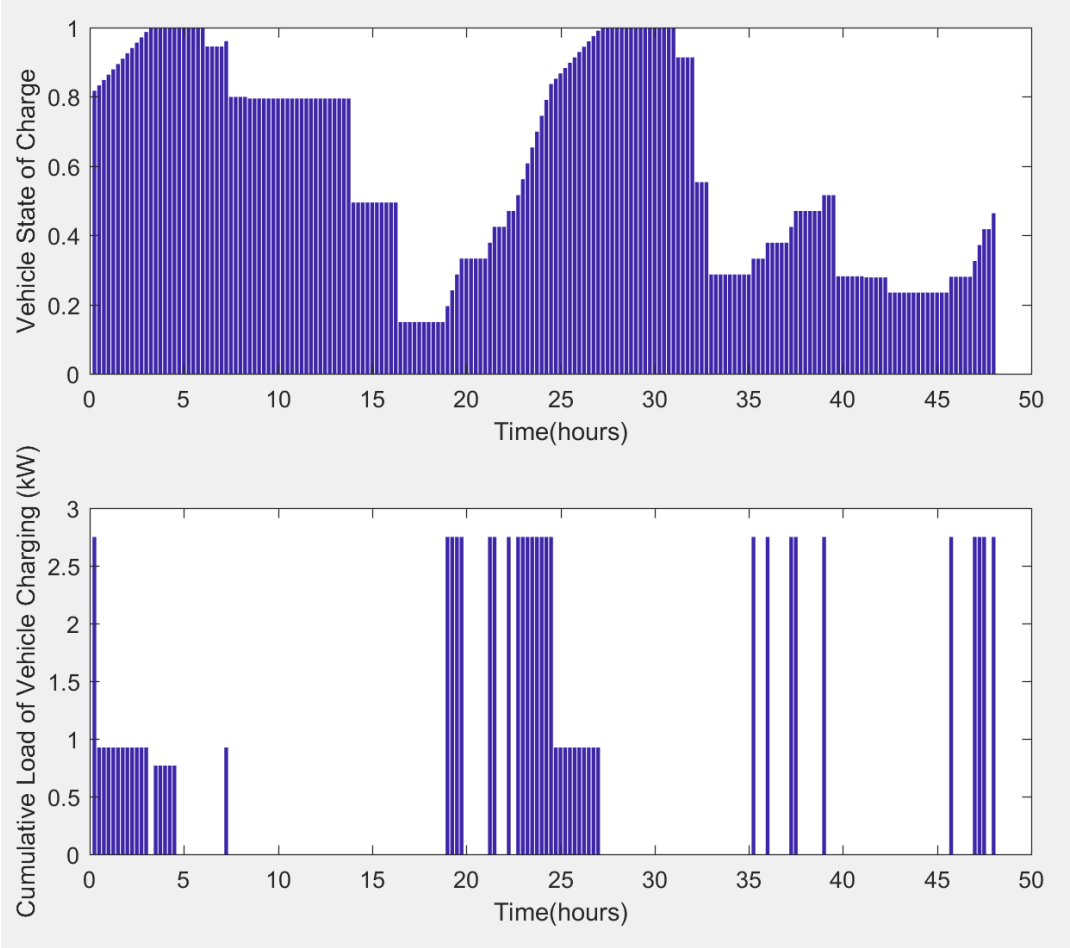


Figure 18: Load results for Level 2 Charger

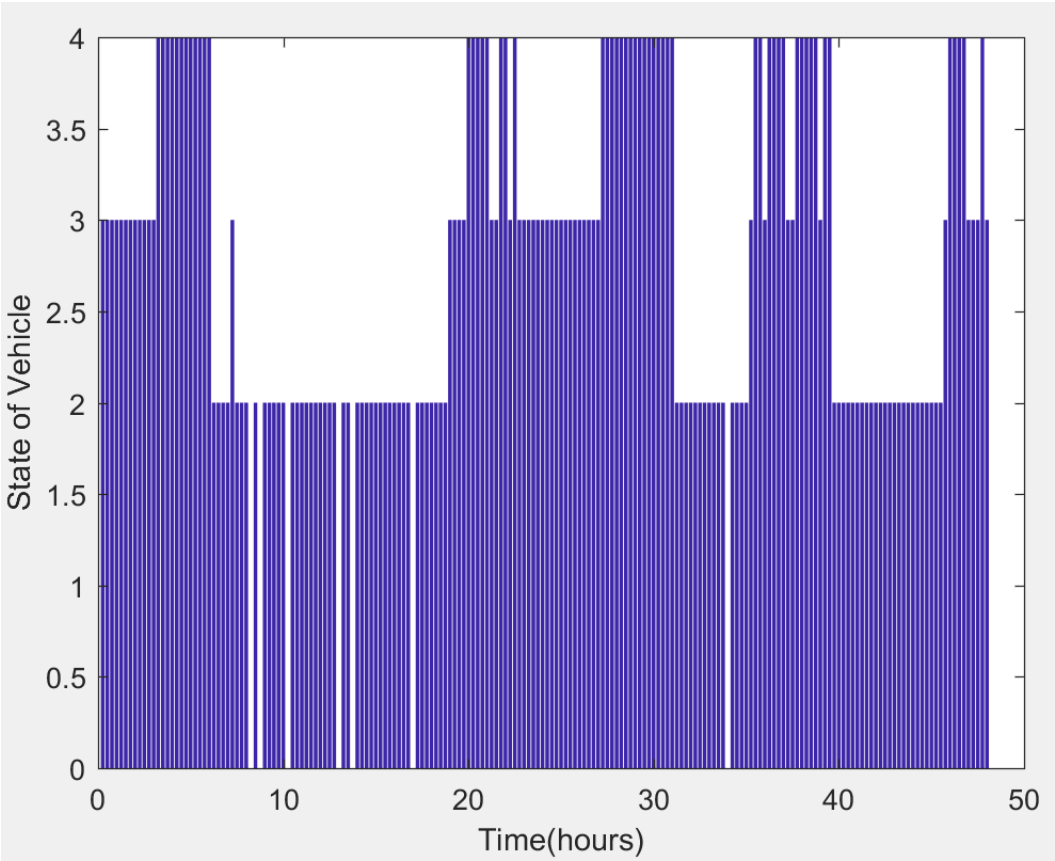


Figure 19: Vehicle state results for level 2 charger

Level 4

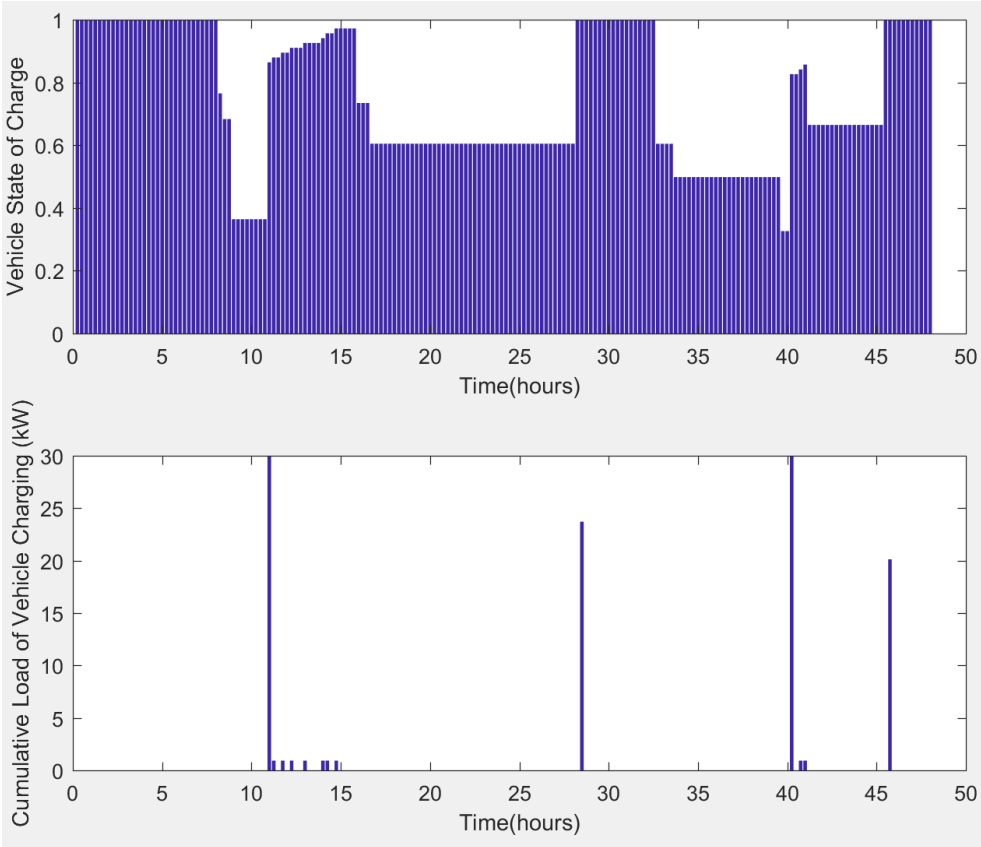


Figure 20: Load results for level 4 charger

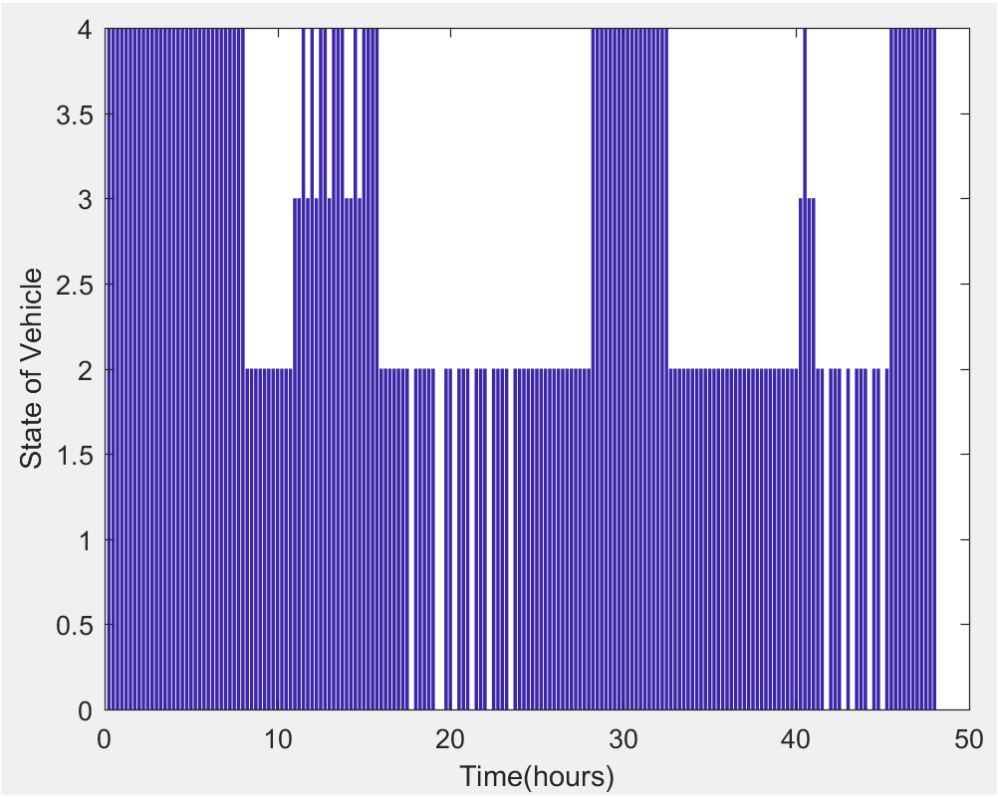


Figure 21: Vehicle State results for level 4 charger

100 Vehicles

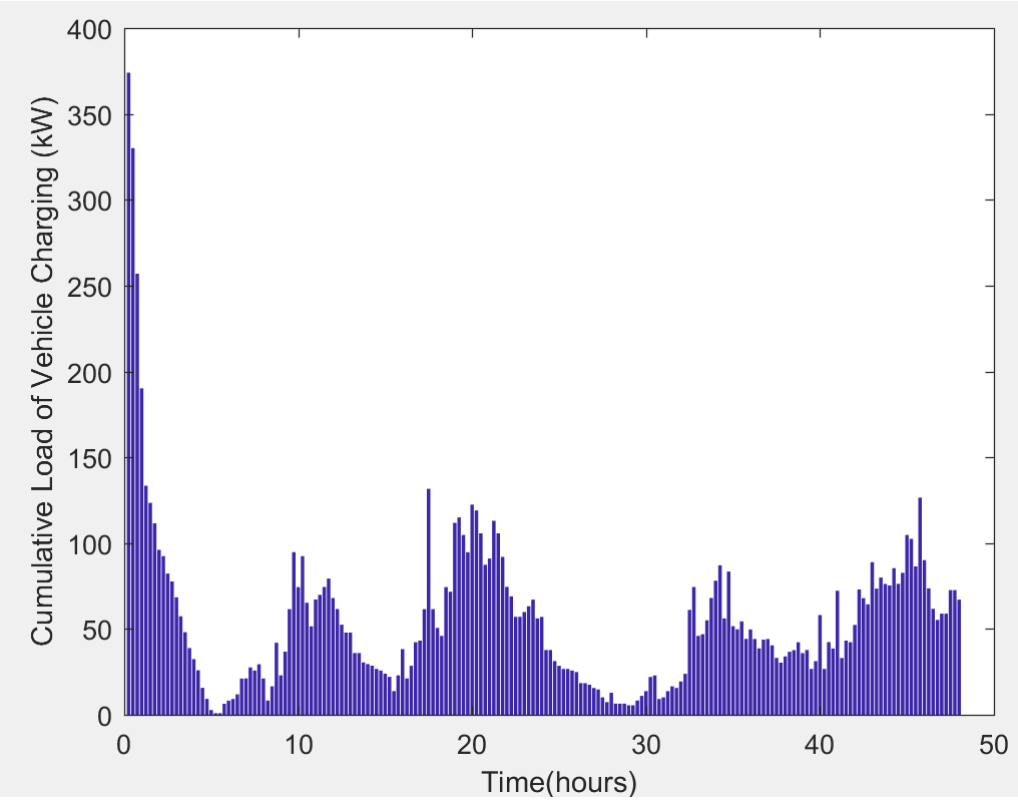


Figure 21: 100 vehicle cumulative loading with improved program

Improved Program Results

After reviewing the results generated by the improved program, the benefit of including multiple levels of charging is clear. Use of the original 11kW power input required hours for a vehicle to become fully charged, whereas using the 22kW significantly reduces this waiting time and using the 145kW input reduces this to within two iterations (30 minutes). The effect of applying the high power charging limit when the SOC is greater than 80% is evident, the charge time is increased and is well displayed in Figure X between 12PM and 3PM. Whilst this will greatly impact the length of time required to obtain 100% charge for the higher power inputs, it should provide a significant benefit to the battery's operational lifetime whilst not having too great an impact on everyday usage of the EV. If 100% battery is a necessity for a trip then a bypass method to enable quicker charger would be necessary.

The improved program provided results of new charging methods, however, with no charging strategies in place there is still uncoordinated charging that has the potential to cause damage to grid infrastructure. In fact, with higher power inputs there is the potential for more concentrated peaks in the demand due to the higher power inputs that are being used over a shorter period of time, this can be seen through comparing the 100 vehicle graphs of the basic

and the improved programs. This shows that with the implementation of high power charging, methods to control EV charging will become even more crucial.

5.4 Charging Strategies

The results generated from both the improved and basic programs clearly display the threat tha uncoordinated EV charging poses towards current grid infrastructure. Without some form of control, users will be capable of disrupting the power system through the simple means of doing what has been done with all rechargeable battery products, charging when it has low power, and will be unaware of the consequences that would occur if this were to be done on a large scale.

To counteract this issue, one potential promising solution is the use of charging strategies for EVs. These charging strategies can be used to regulate what time periods individual customers are able to charge their EVs. Of course, exceptional cases will be necessary for when customers strictly require their EV to be charged, although assumedly, energy companies will have charges incurred for these scenarios. Whilst this may sound cumbersome and controlling for the customer, the energy companies will likely apply low cost tariffs for charging EVs during ideal times as this will enable maximum usage of intermittent energy sources when they are available.

Often, these times of low energy are during the night when the demand for domestic power decreases significantly. This presents an opportunity to charge EVs during the night which will present the customers with a fully charged vehicle in the morning.

However, in order to maintain grid stability, the number of customers that obtain these charging strategies will be selected by the given energy supplier as, if all EV users were to charge during the same hours, this could create new peaks in energy demand greater than the current domestic peaks. Due to this, fractional EV charging strategies would likely be necessary.

Scenarios

Scenarios were developed to best display the potential use of using EVs to offset the domestic peak power demand as well as removing the risk of new EV peak demands. Figure X shows the average daily domestic demand [49], it is clear, that the trough in the demand occurs roughly during the hours of 12AM till 6AM. Thus, the improved program was given the capability to implement charging strategies during selected time periods for a given fraction of vehicles. Table X below shows the chosen scenarios that were simulated. Each scenario was ran for 100 vehicles over the 48 hour period and the cumulative loading due to the vehicles with applied charging strategies can be seen in Figure X.

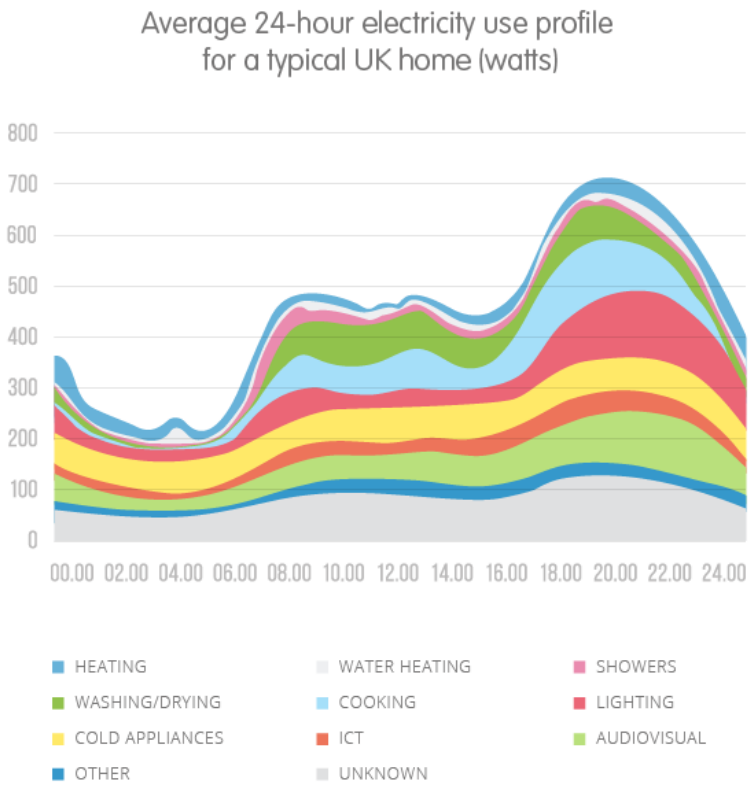


Figure 22: Daily domestic power demand [49]

Table 1: Charging levels of electric vehicles [30]

Scenarios	Charging Strategy
25% of vehicles	12AM-6AM
50% of vehicles	12AM-6AM
75% of vehicles	12AM-6AM
100% of vehicles	12AM-6AM

Charging Strategy Results

From analysing the results shown in Figure X, the consequences that applying charging strategies to all EVs would have upon the power grid are evident through creating large peaks in demand that were inexistent prior to EV application. The small amounts of demand found during the 100% charging strategy simulation were caused due to EVs attempting to make a trip but not having sufficient charge. This represents the small amount of EV loading that would occur due to customers being willing to pay a surcharge to charge their vehicle for necessary trips that would otherwise not be possible.

It is clear that in reality, charging strategies will have to be devised for each concentrated location of EVs. However, in doing so energy suppliers will have the opportunity to reduce the difference between peaks and troughs of daily domestic energy demand whilst also reducing the requirement for upgrading grid infrastructure.

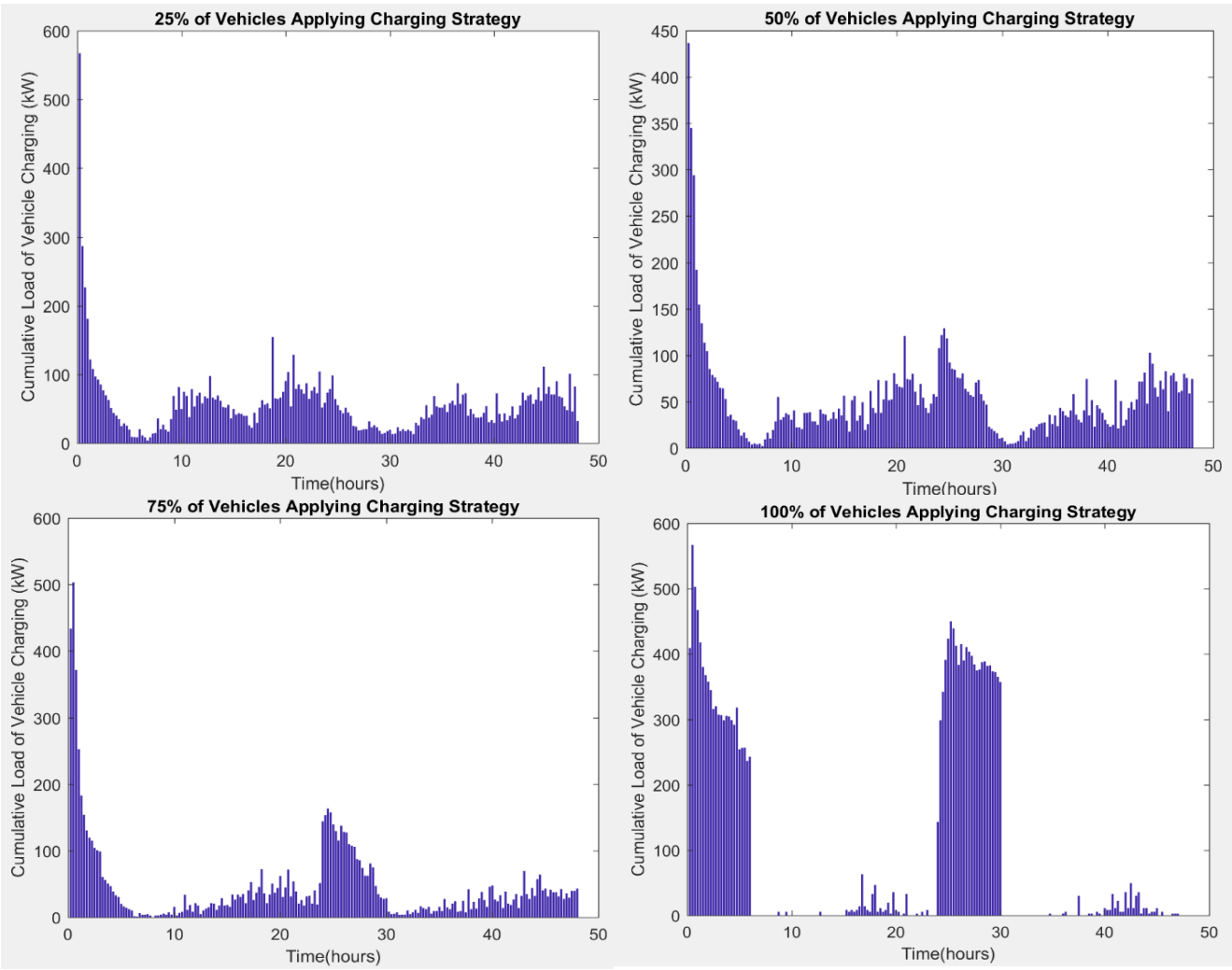


Figure 23: cumulative loading for different fractions of charging strategies

5.5 Vehicle-to-Grid

Controlling EV charging has the potential to provide another benefit to energy suppliers by using EVs as distributed forms of energy storage and generation. This concept has the exciting possibility of solving the grids current and future need for energy storage systems, as the penetration of intermittent forms of energy generation increases. Referring again to Figure X above, EVs could be used to store excess energy generated during the off peak hours between 12AM and 6AM but could also be used to reintroduce energy during peak demand hours between 5PM and 9PM.

This concept could be proposed to customers as a method for further reducing their energy bills as they would no doubt receive payment for every unit of energy that they resupply the grid with. It shows great promise for energy suppliers as this would provide on-site energy generation, reducing transmission losses that would otherwise have occurred. Not only this but lithium-ion batteries tend to have a higher energy exchange efficiency than current methods of energy generation, especially in comparison to renewables. This concept is exceedingly ideal as if the vehicle has sufficient charge to be able to discharge during peak hours, these are some of the times of lowest trip probability as people are at home for the evening, hence the peak demand.

Vehicle discharge was simulated below for the 85kWh vehicle, the conditions set were as long as the vehicle's SOC was greater than 60% during the hours of 5PM and 9PM of the first day then the vehicle would discharge at the same rate as its applied charger.

The results of the vehicle to grid simulation are shown in Figure X and the discharge is displayed as the negative load that is applied. Due to the methods used to calculate the cumulative loading from numerous vehicles, the discharge of vehicles is not noticeable and so in future, a different method for plotting the discharge of vehicles alongside their charging would be of interest.

Whilst the current capability of the program to model vehicle-to-grid interactions is limited, there is clear potential for this concept to be applied on a larger scale for further benefit to both the energy supplier and the EV owners. This can be seen through reducing total energy costs by improving the current daily energy demand profile to a flatter and more efficient profile.

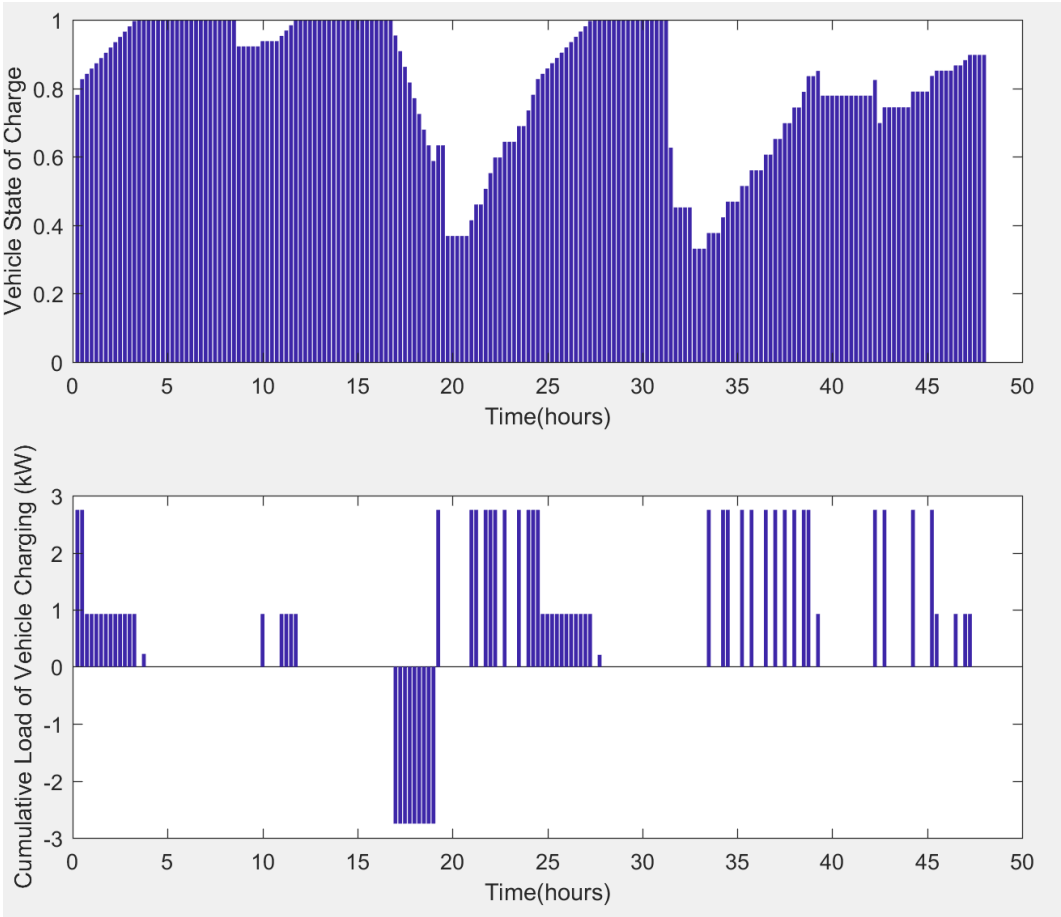


Figure 24: Load results for vehicle -to-grid scenario

6. Conclusion

This project was carried out to develop a program capable of modelling electric vehicles and the load they generate due to charging. The program was developed using Matlab and introduced a number of vehicles and methods of charging. To generate an estimated loading for each vehicle, probability functions were applied for the occurrence of trips and the distance of each of them.

Whilst this program introduced three different battery capacities to represent three types of vehicles, this still does not accurately represent the number of varying EVs that are available even in today's market. This could be improved through introducing even more variance within the vehicle selection. Other areas that could have been improved in the project are the distance generator which applies a linear random multiplier against the average distance of trip which was found to be 65 miles. This does not accurately represent real distances covered by vehicles as there would most likely be a Weibull distribution applied to the distances. However, applying a Weibull distribution would reduce the average distance covered by vehicles and thus, the average loading applied to the grid. So use of this linear randomness applies more loading on the grid which means it could be used as a worst case scenario.

The program generates an initial SOC for the vehicle, through analysing any of the cumulative load graphs above for multiple vehicles, it is evident that this applies unrealistic loading during the first few iterations. This is an issue that should be improved within the program, however, the simulation covered a 48-hour period and so any analysis carried out should disregard this peak when drawing results from the graphs.

Whilst these assumptions could have been improved to better the final results of the program, their application was necessary to generate the estimated results within the time required of the project.

Through developing this program, this project was able to clearly demonstrate the significant impact and damage that EVs could cause to the current power grid if appropriate prevention measures are not applied. The graphs of the uncoordinated vehicle charging show that EVs left unmonitored could increase the peak domestic demands significantly. Thus, coordinated charging/charging strategies are necessary in the future to ensure the integrity of the power grid and security of supply to customers.

This project displayed simple yet effective charging strategies that can be applied to electric vehicles through a charging contract that enables power companies to specify periods during

which charging would be allowed for customers. Through applying charging time restrictions, power companies will be able to prevent increased loading during peak times of demand. They will also be able to increase the trough of demand that occurs during the night by charging vehicles during these hours. This should increase the power supply baseline and enable more low-cost energy sources to be utilised.

The energy supply could be further improved using EVs through implementing vehicle-to-grid energy generation. This would enable fleets of EVs to be used as distributed energy storage and generation to balance load changes as they occur throughout the day. Simulations carried out during this project demonstrated a potential method by which energy companies could implement controls for this concept to beused.

If programs such as the one developed for this project are used to forecast and simulate EV application, any potential issues or impacts that could occur from their implementation could be negated and could even provide over-all benefits to both the energy supplier and their customers.

7. Future Work

There is little doubt that electric vehicles will be the next significant form of transportation. This presents both a huge opportunity and challenge for the energy sector in handling such developments. Using programs such as the one created for this project to model future scenarios will enable them to become better prepared for such drastic changes to the power system. However, the work carried out in this project only covered a small fraction of the over-all problem. In order to be better prepared, it is expected that further analysis would be required. Some of the key areas that could be developed for this software are discussed below.

Combined Household and EV Load Simulation

One of the main areas that would benefit from future research, would be to apply the EV models to the energy demand of domestic households. Including such a function would enable the model to simulate both demands and then manage them effectively to provide the best charging strategy for the EV which will compensate for the household demand.

Distributed Generation

Distributed energy generation could also be included within this program. Applying distributed energy generation to EV loading would enable for renewable energy sources to supply households with even more energy through supplying the EV with any excess energy. This would enable these cheap sources of energy to be used at point of generation instead selling power to the grid, which would incur transmission losses. Having this system in place would further encourage EV users to purchase their own form of energy generation due to the savings that would no doubt occur.

Energy Storage

Developing the use of EVs as energy storage systems and furthering their potential to supply vehicle-to-grid energy would provide useful simulations to estimate the effectiveness of a fleet of vehicles as schedulable energy storage devices.

Network Analysis

If EVs are simulated alongside households and distributed generators, there would be the potential to develop realistic network models to design future power systems. This could be a powerful tool for energy companies to best design their power systems to minimise losses and provide more secure energy to their customers.

Case Study

If the above ideas are further developed alongside a program similar to the one created for this project, this could be used for a future project to be applied to a case study. With cities developing their EV infrastructure, the need for case studies to be carried out is growing as they will help guide the way for future energy systems.

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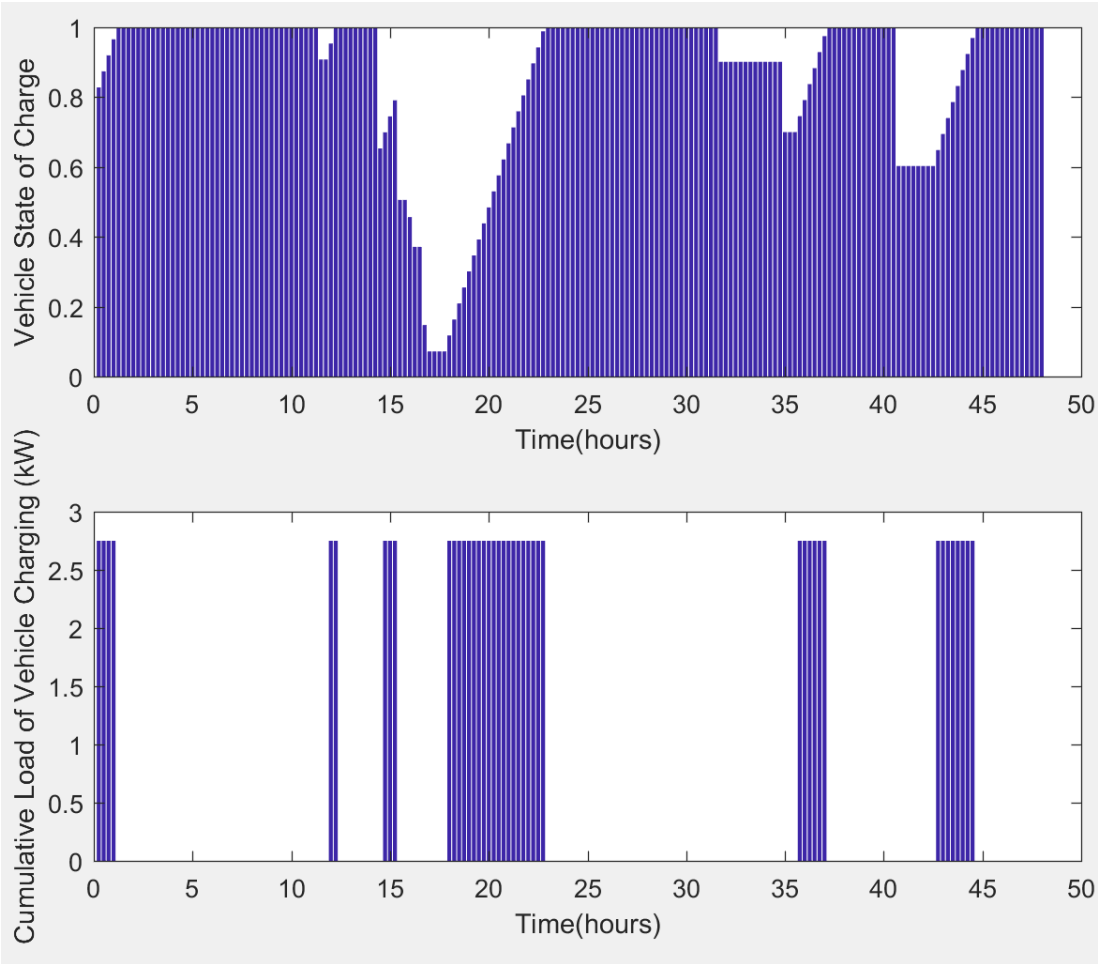
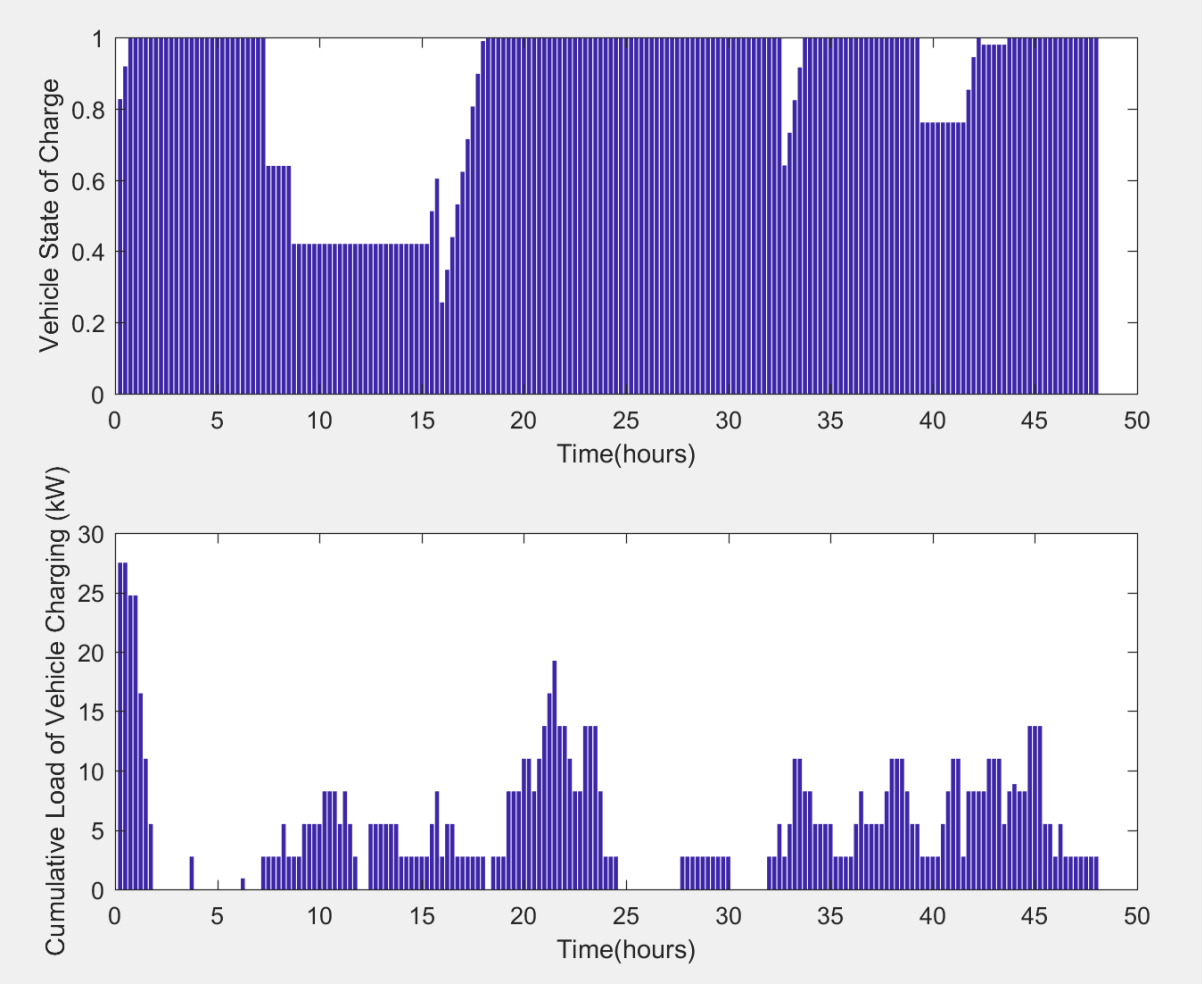
9. Appendices

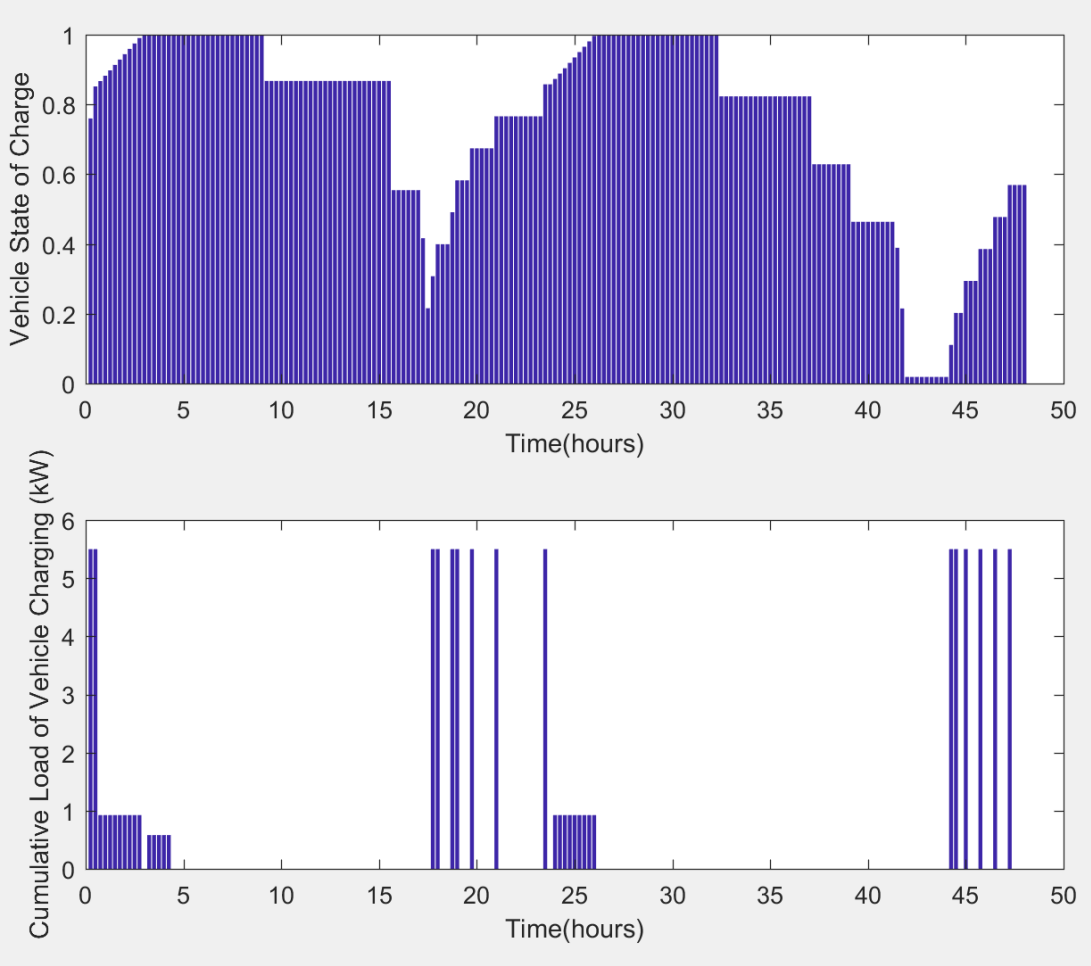
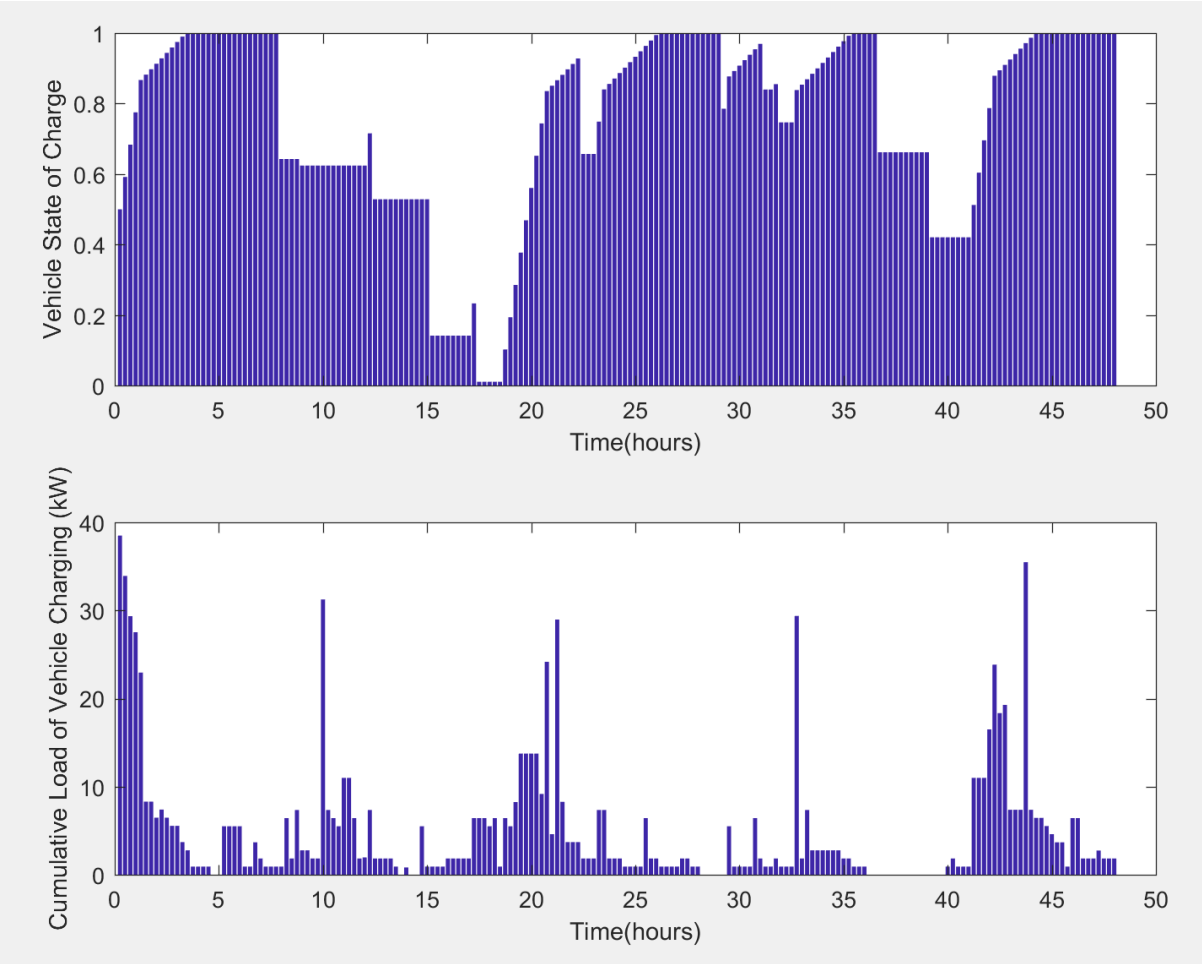
Appendix A - Results for basic simulation of 60 kWh EV



Appendix B - Results for cumulative loading of 10 EVs during basic loading



Appendix C – Results for applying level 3 charging to EV



Appendix D – Results for cumulative load of 10 vehicles within improved program