A Study of the Impact of Electrification of Auckland's Bus Depots on the Local Electricity Grid

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Final report – Public Version

Report prepared by:

elementenergy

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Executive Summary

Context

As part of a wider low carbon agenda, Auckland plans for all new buses to be zero-emission by 2025 and for the whole bus fleet to be zero emission by 2040. To achieve these targets Auckland Transport commissioned a low emission bus roadmap which was completed in January 2018 and is in the process of trialling electric buses, with the first two already on the road. One of the key recommendations of the low emission bus roadmap was to conduct further work to understand the "technical, practical and cost implications for large scale zero-emission bus charging on the local electricity distribution network". As a result of this recommendation, Auckland Transport and C40 Cities commissioned Element Energy to conduct this piece of work focused on providing more information on the grid sizing and cost implication of introducing electric bus depots.

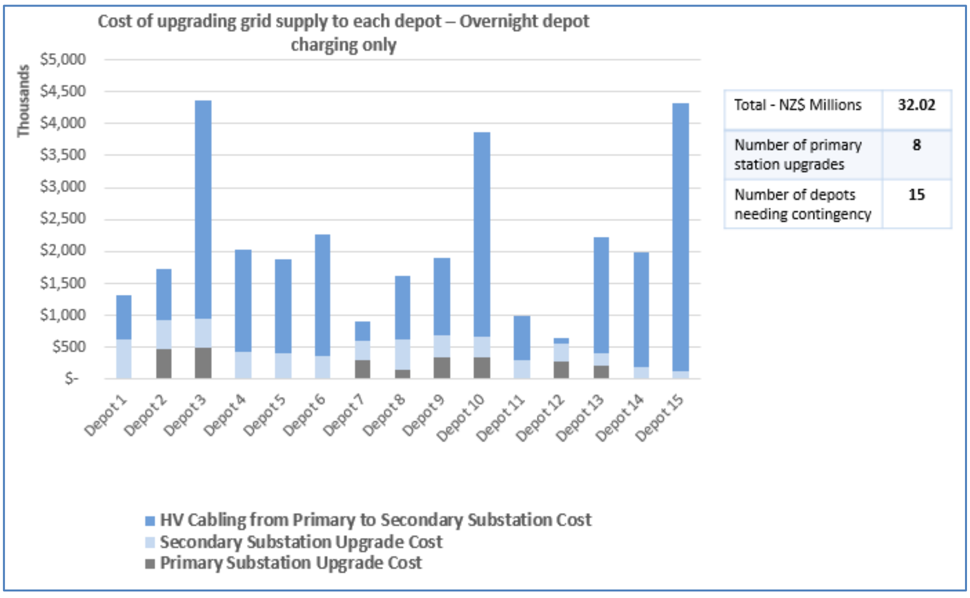
Objectives

More specifically Auckland Transport wishes to understand the peak power demand and grid upgrade costs for each of the main 15 bus depots in Auckland, if they were converted to 100% electric buses. This has been achieved through modelling electric bus charging and grid upgrade requirements based on bus fleet data (provided by Auckland Transport) and electricity grid data (provided by Vector, Auckland's Distribution Network Operator). Other electric bus projects around the world have demonstrated that grid costs can be a significant proportion of total bus fleet electrification costs and that converting the whole fleet to electric buses can be very challenging. Therefore, this work also reviews mitigation strategies for reducing peak charging power demands and costs, and presents an initial Auckland bus fleet electrification plan. These last two objectives of the work aim to support Auckland Transport in their next steps towards bus fleet electrification by highlighting areas where further work should be focused.

Results – overall baseline cost and electrification plan

The work found that significant investment (up to **NZ$32 million**) in the Auckland electricity grid is required for the introduction of electric bus fleets. The figure below summaries the grid upgrade costs per depot for depots using overnight depot charging only. This highlights the wide range of costs between depots, suggesting some depots such as Depot 12 are far easier to prepare for electric buses than others, meaning some depots will require significant support to achieve the switch to electric buses.

The grid upgrade costs for an electric bus depot can be split into substation upgrades (resizing of transformers etc. to allow the substations to cope with the higher peak load) and cable costs (a new high voltage cable must be lain from the depot to the nearest primary substation to connect the depot). In New Zealand where electricity demand is geographically dispersed a single primary substation can supply a large area. This means the length of the new high voltage cable is often relatively long (1-3km). This combined with high cabling costs caused by the difficulty of



laying the cable underground in the local volcanic rock results in the cabling costs dominating the overall grid upgrade costs for the Auckland bus depots.

The electrification of a bus depot is easier for bus operators with multiple depots as this provides flexibility to move buses between depots and electrify whole depots at a time. This can lead to significant costs saving as electrifying a single depot in stages increases total grid upgrade costs. Based on bus operator flexibility (from having multiple depots) and the cost results from the previous figure a phasing for the introduction of electric bus fleets has been suggested in Table 1 (Phase 1 to 3 covering early to late implementation respectively).

- Bus fleets suggested for **Phase 1** are those with relatively few buses in the depot, low to medium grid upgrade costs and bus operators with more than one depot. These depots should be the focus of Auckland Transport's next stage of analysis as a number of these should be viable for early electric bus testing and fleet integration.
- **Phase 2** is made up of depots where bus operators will require additional support from Auckland Transport either because of the, higher costs or increased challenges for a single depot operator.
- **Phase 3** are depots with large fleets and high grid upgrade costs. It has been suggested that these depots are left till last because future changes such as grid upgrades completed to support the introduction of electric cars could lead to reduced costs making it easier to electrify these fleets.

Table 1 Electric Bus Phasing Schedule

Operator	Depot (anonymised)	Number of Buses	Distance to Primary (km)	Grid Upgrade Cost (NZ$ million)	EV Introduction Phase
Operator 1	Depot 1	152	0.7	1.3	2
Operator 2	Depot 2	111	0.8	1.7	2
	Depot 12	66	0.1	0.65	1 (Testing)
Operator 3	Depot 3	113	3.4	4.4	3
	Depot 5	98	1.5	1.9	2
	Depot 6	91	1.9	2.3	2
	Depot 9	81	1.2	1.9	2
	Depot 11	71	0.7	1.0	1 (Testing)
	Depot 13	47	1.8	2.2	1
	Depot 14	46	1.8	2.0	1
Operator 4	Depot 4	102	1.6	2.0	2
	Depot 15	27	4.2	4.3	3
Operator 5	Depot 7	86	0.3	0.91	2
Operator 6	Depot 8	85	1.0	1.6	2
Operator 7	Depot 10	81	3.2	3.9	3

Cost mitigation options

These high upgrade costs can be mitigated to an extent using a number of mitigation strategies such as: smart charge management, opportunity charging (whereby a bus partly charges at the end/start of a route, outside the depot), timed tariffs and on-site energy storage/generation. A high-level assessment of the cost reduction brought by opportunity charging has been conducted. It was found that the previous figure of NZ$32 million could be reduced to **NZ$16million.** However, this reduction relates to the depot grid reinforcement cost; opportunity charging might also trigger some grid upgrade costs outside of depots, and the chargers themselves are most costly than depot-based chargers.

Next steps

To properly understand the full value of mitigation strategies, an in-depth analysis of each depot is required, which the data gathered for this study could not support. It is suggested that Auckland Transport carries out this analysis as their next step in electrifying the bus depots.

This analysis should start with a few depots (Phase 1 depots are well suited) and aim to fully specify and cost the project (including selecting bus models, sizing bus chargers and analysis of mitigation strategies such as opportunity chargers).

To achieve this level of detail, this work should include the **key stakeholders** (bus operators and Vector). To fully specify and cost each depot significant amounts of fleet operating data is required (e.g. required e-bus range and passenger capacity, route topography, heating and cooling needs, space to locate chargers and potential charging windows). This work has highlighted driving demand (km) and charging windows (hours) as two factors that should be understood in-detail as the grid costs are very sensitive to changes in these parameters – these parameters are best understood by bus operators themselves. Vector will also be an important stakeholder, to refine the reinforcement costs, especially around the cabling distance.

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Acronyms

AT	Auckland Transport
BEV	Battery Electric Vehicle
DNO	Distribution Network Operator
EHV	Extra High Voltage
HV	High Voltage
LV	Low Voltage
LowCVP	Low Carbon Vehicle Partnership
PHEV	Plug-in Hybrid Electric Vehicle
PPD	Peak Power Demand
TRL	Transport Research Laboratory
VDAM	Vehicle Dimensions And Mass

1 Introduction

1.1 Background

As part of a wider low carbon agenda, Auckland plans for all new buses to be zero-emission by 2025 and for the whole bus fleet to be zero emission by 2040. To achieve these targets Auckland Transport commissioned a low emission bus roadmap which was completed in January 2018 by the LowCVP and TRL and is in the process of trialling electric buses, with the first two (ADL/BYD single decker buses) already on the road. One of the key recommendations of the low emission bus roadmap was to conduct further work to understand the "technical, practical and cost implications for large scale zero-emission bus charging on the local electricity distribution network". Providing information to fill this knowledge gap is the aim of this report.

1.2 Objectives

The objectives of this work to meet the overall aim of understanding the grid impacts of electric bus charging are:

1. Calculate the depot peak power demands caused by bus charging at each of Auckland's current bus depots.
2. Calculate the grid upgrade costs caused by bus charging at each of Auckland's bus depots.
3. Report on the range of mitigation strategies that could be deployed to reduce the peak power demand and grid costs at Auckland's bus depots.
4. Report on how electric buses could be phased into the fleet and how this will affect other fleets ability to transition to electric vehicles.

1.3 Scope

The scope of the study covers 15 depots for the case where all buses would be replaced by pure electric buses and covering the same operations than they do now (same mileage per day, from same depots, with the same number of buses). The upgrade cost estimates cover the grid assets related to the depots, not other locations (e.g. opportunity charging outside of the depot), nor the charging equipment itself.

1.4 Structure of the report and other deliverables

The next chapter describes the Auckland bus fleet and the model developed for the propose of this study. The key assumptions used in the model are outlined and justified, and the limitations of the model are made clear.

Chapter 3 presents the results of the analysis conducted with the dedicated modelling tool. It outlines the peak demand at each of the depot in scope for the case of 100% electric buses, compares it to the available spare capacity on the local grid, and gives the related grid cost upgrade estimates. The results of a sensitivity analysis are also included in this section.

The last chapter makes recommendations in terms of the next steps to refine the analysis. A prioritisation of depots in terms of electrification is provided, taking into account mitigation options to decrease the local peak demand (such as opportunity charging).

This report is one of three deliverables of the study, the other two deliverables are:

- The aforementioned model (Excel file) that holds the bus depot data and calculates the peak demand and grid cost upgrades
- A slide-based report about the basics of electric bus charging, covering bus charging technologies (overview of charging types, as well as trends observed in Europe), the grid infrastructure (the electricity network and the components relevant to electric bus charging) and electricity tariffs (tariff structure and the changes bus operators adopting electric buses might expect).

2 Modelling Auckland bus depots power demand

This chapter describes the approach taken to estimate the power demand of fully electrified bus depots. A modelling tool was specifically developed as part of the study and is a key deliverable of this work; it is referred to as ‘the bus depot model’ or simply ‘the model’ in the subsequent text.

2.1 Overview of the bus depot model

The model focuses on fifteen bus depots in Auckland – shown in the map below and listed in the Appendix (Table 6). It calculates the individual peak power demand, and the resulting costs of upgrading the electricity network to accommodate this increase in demand, for each bus depot assuming the entire fleet is converted to electric buses. The Excel-based model comprises of six main modules (tabs) as listed below;

User control panel: allows the user to input information regarding depot charging, opportunity charging and infrastructure costs. For example, charging window at the depot (hours).

Peak power demand calculation: this is the calculation tab which calculates the peak depot power demand without opportunity charging, peak depot power demand with opportunity charging and the grid infrastructure upgrade costs related to depot charging.

Network Input: this tab contains information on the location, size and spare capacity of the primary substations that currently supply the bus depots.

Electric Buses: this tab holds data on the energy efficiency (kWh/km) of electric buses over a selection of route types (973, Inner Link, City Link). The data mainly comes from the TRL modelling.

Bus Information: this tab is a record of the bus data (number of buses, annual distance driven, number of single and double deck etc.) for each depot. The data comes from Auckland Transport.

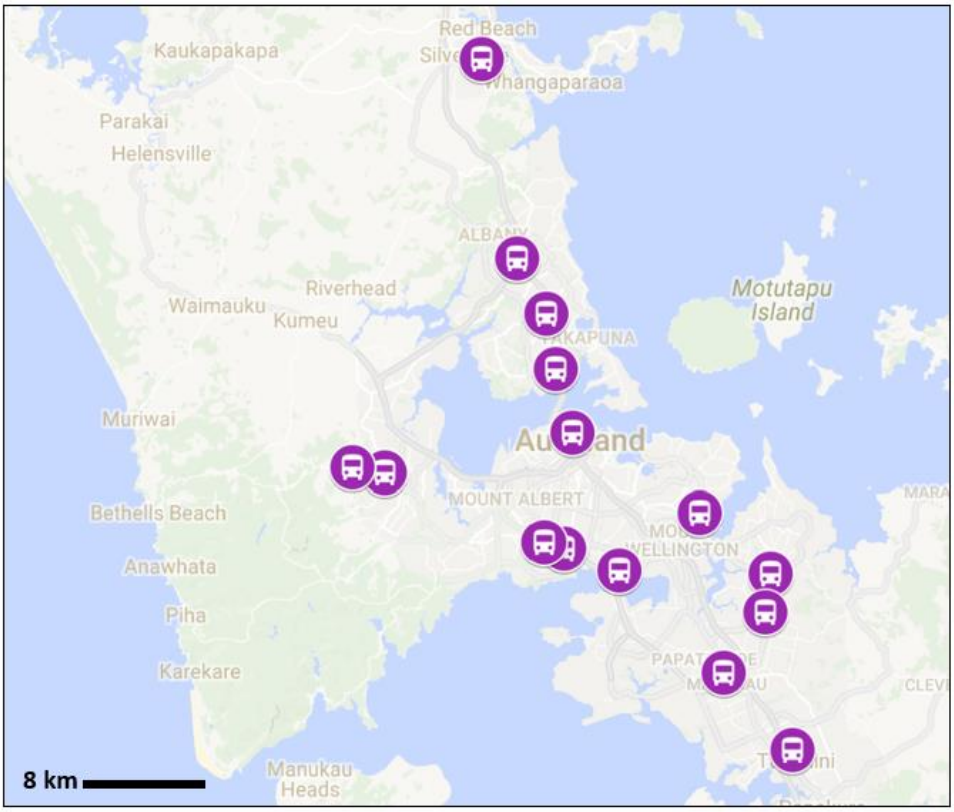


Figure 1 Bus depots included in the modelling tool developed for the study

2.2 Peak power calculation

2.2.1 Depot only charging

The peak power demanded by the bus chargers in an electric bus depot is an important parameter to understand when designing the charging system. This is because the peak power demand sets the required sizing, and therefore, costs of the electricity infrastructure needed to supply power to the chargers. As this is one of the most expensive aspects of installing a fleet of electric buses, it is important to understand the peak power demand early on in the electric bus depot design.

An overview of the calculation process used to calculate the peak power demand is given in Figure 2. The first step of the calculation process is to calculate the average power demand throughout the night. This is calculated in the **Core** sub-model and is a function of the four parameters numbers below.

1. Average daily distance travelled per bus
2. The number of buses in a depot
3. Average electricity consumption of buses (which in turn is a function of the share of single / double decker buses and route type)
4. The charge window in hours

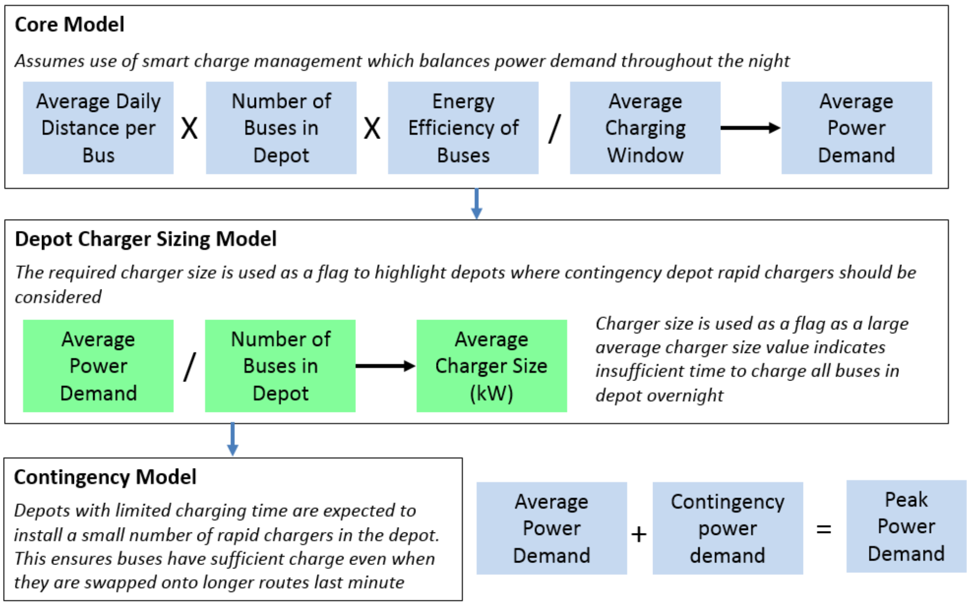


Figure 2 Overview of the peak power demand calculation

This calculation assumes that the charge given to the buses in the depot at night is exactly equal to the energy used by the buses during the day and that the buses are charged at a constant rate for the full charging window. This means the buses are not all put on to charge at the end of the day and charged quickly, in the first half of the charging window, but are instead charged at a slower rate to use the full charging window or are charged in shifts (e.g. 10 buses charged for two hours and then the next 10 and so on). This second assumption assumes the use of smart charge management to control bus charging speeds or to charge buses in shifts. This is considered a fair assumption as smart charge management is being used widely across the industry and is now available as a standard feature on many depot chargers[1]. Smart management is a cost-effective solution as it allows depots to avoid significant electricity network upgrade costs. It is, therefore, assumed that all bus depots moving to electric fleets in the future will make use of this technology.

The average power demand figure represents most of the power needed by the depot overnight but does not include any contingency to allow for real-world situations where a small proportion of the fleet

[1] ABB, 2017, depot charger smart management. http://www.abb.com/cawp/seitp202/5555b7ac4c17485ec12581c20041c471.aspx

needs to be charged quickly (e.g. a problem with a charger or a bus means a bus needs to be charged quickly in the morning to be ready to operate). To cover these situations, it is common for electric bus depots to have a small number of rapid chargers in the depot. The number of rapid chargers per depot is a user-defined input (default input is 8 rapid chargers per 100 buses in the depot), while the size of the rapid chargers is calculated in the model. Calculating the rapid charger size is a two-step process completed by the **Depot Charger Size** and **Contingency** sub-models (see Figure 3). In the first step, the **Depot Charger Size** sub-model calculates the power rating for the slow chargers in the depot (this is a function of the average power demand and the number of buses being charged). This value is then compared against common bus depot chargers available on the market to access if the charging demand is[2]:

1. **Green Flag**. Depot requires slow chargers **0-20kW**. Common slow depot AC chargers are 22 or 44kW. Depots that require slower charging than this are not time constrained and are not expected to need contingency rapid chargers.
2. **Yellow Flag**. Depot requires slow chargers **20-45kW**. Common slow depot AC chargers are 22 or 44kW. Depots using these size chargers in other cities around the world are often designed with a small number of relatively low power contingency rapid chargers.
3. **Amber Flag**. Depot requires slow chargers **45-65kW**. Chargers over 44kW must be DC, switching to DC comes with a cost penalty, the decision to go over 44kW, therefore, indicates a time-constrained depot. These depots are expected to need more contingency as there is less flexibility within their charging window.
4. **Red Flag**. Depot requires slow chargers over **65kW**. Depot DC chargers up to 120kW are in use in electric bus depots around the world but for the relatively small bus depots and short operating schedules seen in Auckland, this would represent a very time constrained depot. These depots will have no spare time for charging if problems occur and will, therefore, need more contingency charging capability.

The output from the **Depot Charger Size** sub-model is then fed into the **Contingency** sub-model which uses depot slow charger size to calculate a depot rapid charger size. The reason the model selects different rapid charger sizes based on the slow charger size is that the slow depot charger size is an indicator of charging time constraint (a low charger size indicates no time constraint while a high charger size indicates a very time constrained depot). It is the time-constrained depots that are expected to struggle with changes in the charging routine (e.g. a bus arriving late) and it is these depots that will, therefore, need the fastest rapid depot chargers. The sizing of the in-depot rapid chargers is as follows:

1. **Yellow Flag**. Depot rapid chargers rate = **80kW**.
2. **Amber Flag**. Depot rapid chargers rate = **100kW**.
3. **Red Flag**. Depot rapid chargers rate = **150kW**.

[2] The slow charger flag system is designed to inform the user of the feasibility of their inputs. Results outside of the expected range could indicate an error in the input data or a bus depot that is not suitable for a 'depot only' charging schedule. The slow charger flag system is not designed to inform the user of the size of the slow depot charger that they should purchase. This should be decided through an in-depth analysis of the driving demands at each depot. It is important to note that while chargers are available across the full power range covered by the flag system not all buses can use all charger types meaning the buses chosen for implementation will restrict which charger type/power can be chosen.

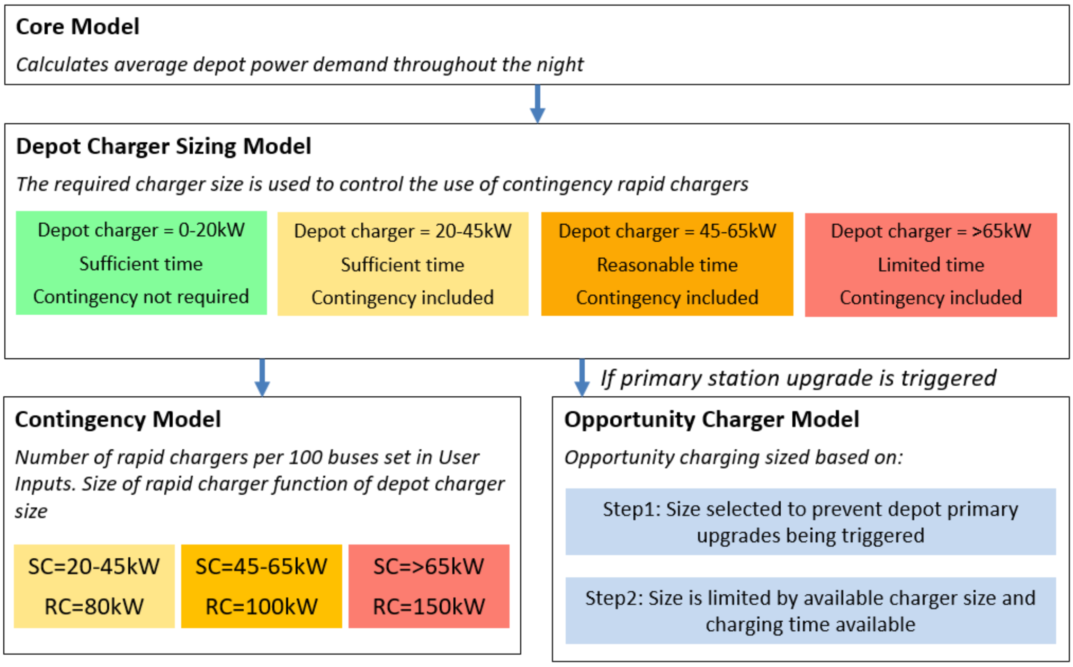


Figure 3 Overview of the deport charger sizing model (SC: Slow charger. RC: Rapid Charger)

2.2.2 Depot + opportunity charging

Opportunity charging (charging at the start or terminus of a route) can be an effective complementary charging technology to night depot charging. The main benefits of opportunity charging are that it allows operators to use electric buses with smaller batteries (thus with lower upfront cost) and it spreads the charging demand out geographically. Spreading the demand helps to reduce demand on individual electricity network assets and thereby helps to reduce grid upgrade costs. The benefits of opportunity charging have been realised by bus operators in Europe, where approximately half of the buses are charged using opportunity charging on top of depot charging.

Opportunity chargers are very expensive (ca. NZ$1million[3]), so they only make sense where charging at the depot is constrained and multiple buses (several buses operating on the same route or several routes that end in a region) can make use of the same opportunity charger. Opportunity chargers can also make financial sense for operators who may be forced to pay for a larger fleet of buses and drivers if only depot charging is used. For instance, if opportunity chargers increase a bus range allowing it to be used for a full day rather than having to go back to the depot to recharge. This would remove the need for another bus to be available to go out and complete the rest of the routes, giving an example where opportunity chargers can improve the economics of switching to an electric fleet. Information on all the routes completed by buses in the Auckland area is not available in this project, and so a detailed analysis of routes where opportunity charging would deliver the most benefit is beyond the scope of this work. However, this will be a vital part of future work that is needed to analyse each depot in detail, to support a decision on the buses and chargers that should be purchased.

However, to help Auckland Transport understand the potential benefits of opportunity charging and to highlight depots where opportunity charging should be first considered, the model includes an **Opportunity Charger** sub-model (see Figure 4). This model calculates the desired level of opportunity charging by assuming that enough opportunity charging will be installed to avoid primary substation upgrades at the depot. This means that opportunity charging is not suggested for all depots, but only for those constrained at the primary level. The outputs of the opportunity charger sub-model are: total opportunity charging energy delivered per day, opportunity charger size and depot peak power demand

[3] Figure based on manufacturer's quote for opportunity charger provided in 2017; does not include grid connection costs.

if opportunity chargers are used[4]. To ensure that the total opportunity charging energy delivered per day is feasible the model calculates the size (in kW) of the opportunity charger required to meet these charging demands. The opportunity charger size is then output from the model with a colour coded flag (this metric is labelled "Implied Opportunity Charger Rate" and is located in the "Peak Power Demand" tab) to advise the user if the opportunity charging demand suggested is feasible. The feedback to the user is designed as follows:

- **Green Flag**. Opportunity charger rate is less than **150kW**.
- **Yellow Flag**. Opportunity charger rate is less than **300kW**.
- **Amber Flag**. Opportunity charger rate is less than **450kW**.
- **Red Flag**. Opportunity charger rate is **less than 600kW**.
- **Florescent Yellow**. Opportunity charger rate is **greater than 600kW**.

Opportunity and flash chargers from 150-600kW are currently on the market and so results in this range are considered possible[5]. The flag system here acts to advise the user about increasing opportunity charger and installation costs, with 600kW chargers costing more than 150kW chargers. The fluorescent yellow flag highlights situations where the suggested charger is over 600kW. The model does not consider this to be a possible solution, so the cell is flagged to tell the user that opportunity charging is not capable of providing enough charge to the buses from a given depot to avoid primary substation upgrades at the depot.

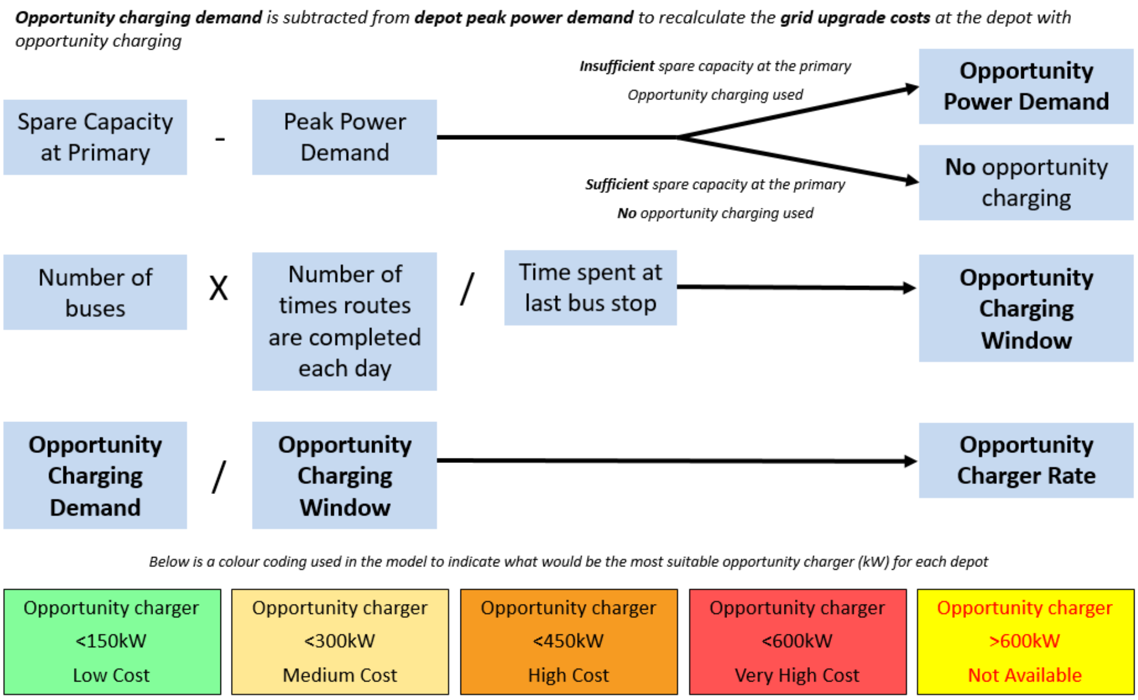


Figure 4 Overview of the opportunity charger model

[4] Opportunity charger costs (installation and grid upgrades) are outside the scope of this work. This is because a detailed study of the vehicles and routes will be needed to size and position opportunity chargers. Before this is completed any analysis of the opportunity charger costs is not possible because the costs can change significantly based where they are placed and how they are used.

[5] Chargers of this power rating are often only used for 5-10 minutes to top up the battery state of charge between routes. If there was no slowing down in the charging rate as the battery reached 100% state of charge, 10 mins at 450 kW would provide 75 kWh. This amount of energy corresponds to about 37km in a single deck pure electric bus.

2.3 Grid upgrade cost calculation

Figure 5 shows a schematic of the transmission and distribution networks. Distribution networks are operated by Distribution Network Operators (DNOs). The DNO for Auckland is Vector. All electric bus depots connect onto the system with a 400V low voltage connection from a secondary substation, this is a similar connection to a commercial supply. Introducing electric buses to a depot can trigger upgrades at the primary substation, secondary substation and the high (11kV) and low (400V) voltage cabling that connects them to the depot. The main component of substations are transformers which step down the voltage of the electricity to safe levels for use in houses and businesses. Vector build their substations from transformers of standard sizes. Secondary substations use 0.1, 0.15, 0.2, 0.3, 0.5, 0.75, 1MVA while primary substations use 20MVA transformers.

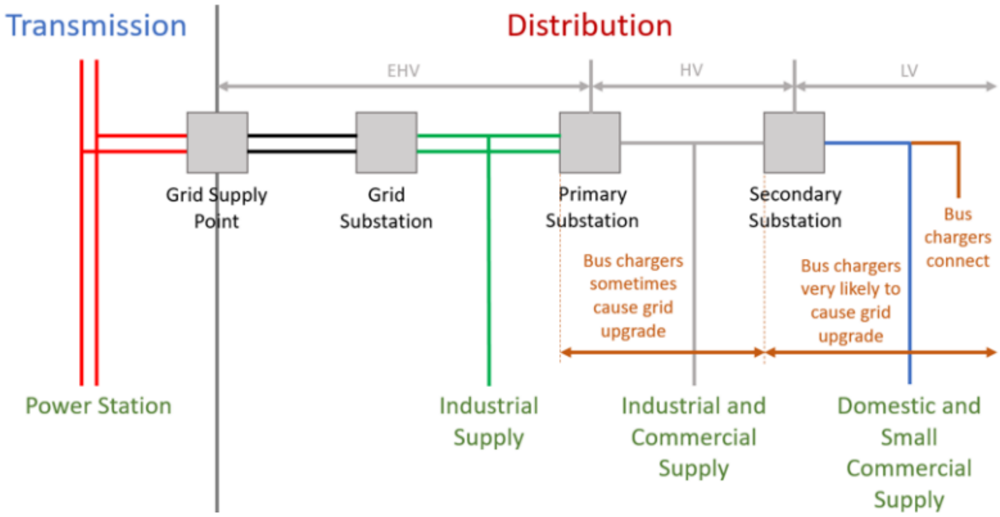


Figure 5 Overview of transmission and distribution networks

Figure 6 shows the unit size of the primary and secondary substations in Auckland against the expected power demand for a 50 and 100 electric bus depot. Most bus depots in Auckland contain approximately 100 buses. At this size, electric bus depots have power demand equivalent to over 1,000 houses. This far exceeds the capacity of the local secondary substation designed to provide power at the residential level. This means that all bus depots converting over to electric buses are almost certainly going to require a new dedicated secondary substation on-site, fed by a new high voltage cable to the local primary substation. Multiple buses charging at a single location can also trigger upgrades to the local primary substation if most of the capacity at the primary is already in use.

Figure 6 also shows the power demand of a large opportunity charger (600 MW). This shows that although each opportunity charger has a very high power demand, their geographic spread means that each substation is likely to only have to support one charger. This means that grid upgrade requirements could potentially be reduced by deploying a strategy that makes use of both opportunity and depot chargers where most appropriate. Grid upgrade costs for opportunity chargers can be minimised by pairing opportunity chargers with energy storage that helps to minimise peak power demand. Designing the cost optimal solution for the charging strategy requires more in-depth information than is available in this work but this should be a key outcome from the in-depth analysis outlined in the Future Work Chapter.

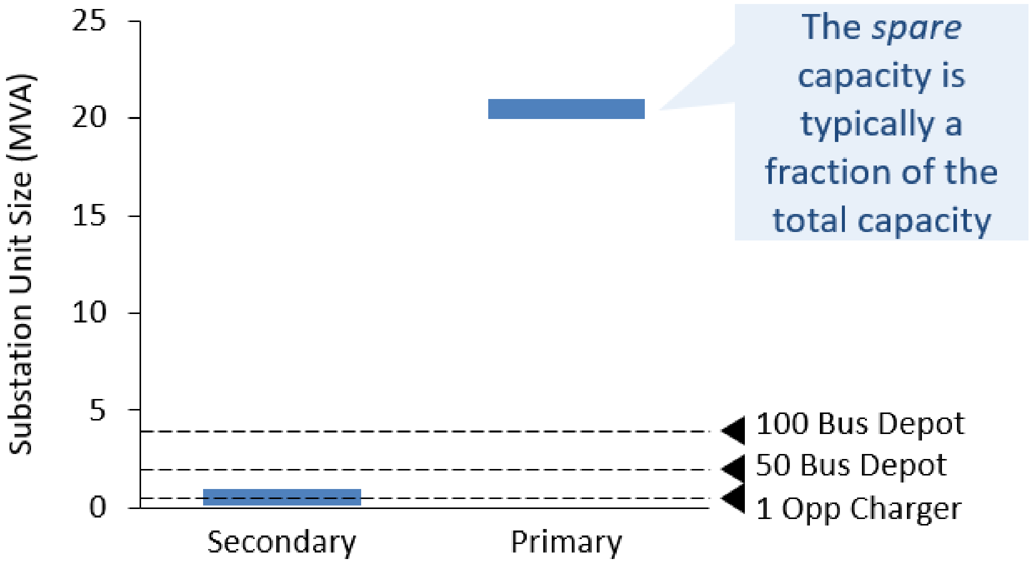


Figure 6 Comparison of substation size to electric bus depot power demand

The model calculates the upgrade costs related to the distribution network upgrade. This cost is made up of two components (see Figure 7):

- the secondary substation and high voltage cable cost, which will be required by all depots
- the primary substation cost, which will only be needed at bus depots where the spare capacity at the local primary substation is constrained.

The model calculates these grid upgrade costs under two scenarios:

- an overnight depot charging scenario
- an overnight depot and opportunity charging scenario. In this case, only the grid costs at the depot are considered, not the potential grid costs related to the opportunity charger(s) as their location is unknown.

The secondary substation upgrade accounts for two factors; peak power demand and distance from the secondary substation to the primary substation. The peak power demand, calculated earlier in the model is used to size the secondary substation and this is converted into a cost based on cost data from Vector. The distance from the secondary to primary substation is required to calculate the length and therefore the cost of installing high voltage cabling from the primary substation to the depot. This distance has been provided by Vector for all the depots in the study.

For most of the depots, Vector has provided information on the two closest primary substations. To select between these two primaries the model calculates the total cost (potential primary upgrade and high voltage cabling cost) associated with choosing each of the primaries and then selects the primary with the lowest total cost for input into the cost model. Primary substation upgrades are only required in the case where the capacity available at the existing primary substation is not sufficient to accommodate the peak power demand of the bus depot. The primary substation spare capacity data used in this project is a snapshot of the situation today. The building of new residential and commercial sites in Auckland as well as the introduction of other electric vehicle fleets and private electric cars will cause the primary substation spare capacity to change over time (both increase and decrease). It is, therefore, suggested that Auckland Transport obtains updated data from Vector about primary substation spare capacity closer to the time at which they are ready to start introducing electric buses. If a primary substation upgrade is required, then Vector will increase the primary size by 20MVA. However, the user who triggers the upgrade only pays for a proportion of the primary upgrade cost in proportion to their use – this is reflected in the mode of calculation (this is common practice in most regions and is defined by the regulatory authority (Electricity Authority in New Zealand)).

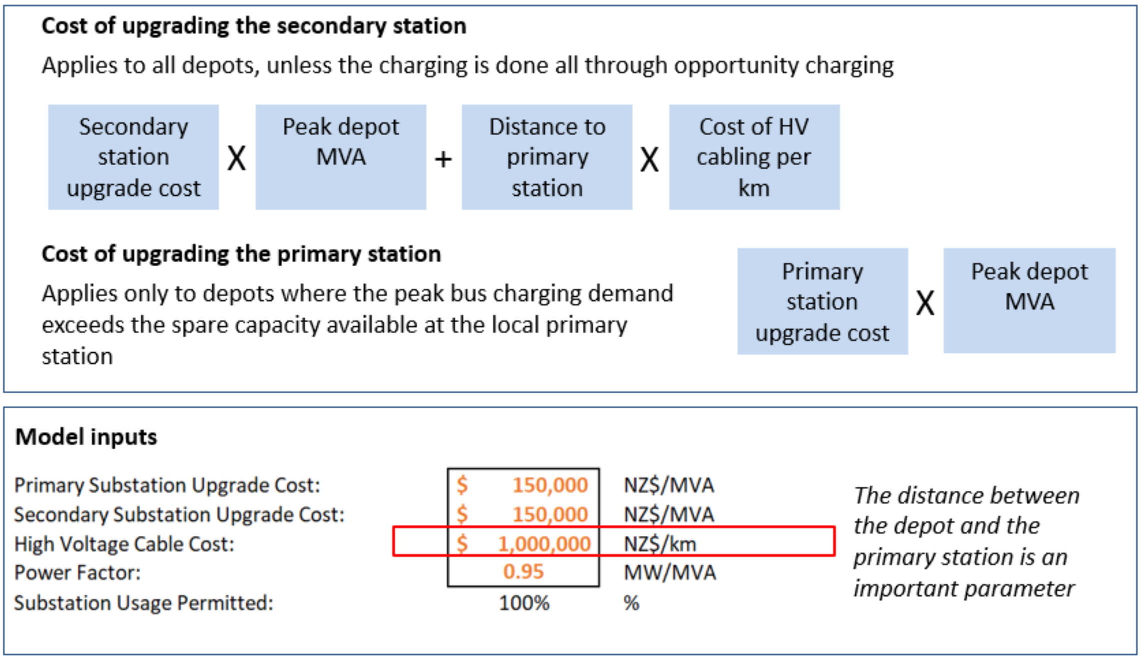


Figure 7 Overview of the grid upgrade cost calculation and related inputs

The network cost inputs are from Vector, the Distribution Network Operator (DNO) in Auckland. The $/MVA values are in line with the values observed in the UK. The high voltage cable costs are much higher than values quoted by UK DNOs (over a factor of 4). This difference in high voltage cable costs is caused by the volcanic geology around Auckland that makes digging trenches for high voltage cabling very challenging and Vector costs are inclusive of all civil works.

2.4 Model limitations

The model is primarily limited by the variation in the bus fleet within a depot, which makes it very challenging to collect accurate average values per depot. The model is particularly sensitive to the charging window, daily distance driven and vehicle fuel consumption. As the average value across the depot for any of these parameters can change in the short (routes may change by the day of the week) and the long (vehicles may be moved from depot to depot) term gaining an accurate value for these inputs parameters is very important but challenging. To help overcome the limitations of the model input data, a sensitivity analysis has been conducted in the Results Chapter to inform Auckland Transport which input parameters are most important, allowing them to focus future data collection efforts. The model has also been designed to ensure it is easy for the user to update input values as new data becomes available. Table 2 explains the quality of data available for each input and the implementation taken to alleviate the data quality issues.

Table 2 Model Inputs, Limitations and Mitigations

Model Input	Data Quality	Implementation in the Model
Number of buses per depot	Up to date information has been provided by AT but data quality is affected by: • Buses regularly move depots • The turnover of the fleet • Data on the split between single/double decker buses in a depot is not always available • Data on the split between small, standard and extra-large buses is not available	The user can vary the number of buses taken into account by changing the "Bus Usage" input in the "User Control" panel. The default value is set at 81%, as per AT recommendation.
Average annual distance travelled per bus	• It has been calculated as the average distance travelled per bus per depot. This will vary from bus to bus and from day to day • In the case of NZ Bus, they provided an average for their overall fleet irrespective of the depot • Birkenhead and Pavlovich provided more accurate information for their respective depots	The user can easily edit these values, as well as apply a +/- percentage change to appraise the impact.
Fuel consumption	• A true average fuel consumption figure is challenging to collect because the value varies from bus to bus and from route to route • The average value for a depot should be weighted by the distance driven but insufficient data was available to achieve this • The model includes a fuel consumption value for three route types, long and short range BEVs, and single and double decker buses	The average value used in the calculations is a weight average taking into account vehicle type (single/double decker) The model also allows the user to input a specific fuel consumption value for each depot
Charging window	• Charging window expected to change significantly for different routes and different days of the week, however there was no reliable data to calculate a charging window specific to each depot • As buses can be charged in shift, as long as the time when the first wave of buses arrives back in the depot in the evening and the time when the last wave of buses leaves the depot in the morning remains relatively constant the model peak power demand estimate will be accurate	A single user defined charging window is applied to all depots, the baseline value is as per recommendation by AT
Time spent at the last bus stop	• Time spent at the last bus stop ranges from less than a minute to over an hour • Value varies by route and bus operator • Value is affected by operating delays	A single user defined time spent at last bus stop value is applied to all routes
Maximum spare capacity of the local primary substation	Data provided by Vector, reflects 2017 spare capacity so necessarily not applicable to future years	The user can update these values with the latest data in the "Network Input" panel. The user can also decrease the spare capacity available through the 'Substation Usage Permitted' parameter
Distance from the depot to the local primary substation	Data has been provided by Vector and has been calculated by following the path from the depot to the primary substation along the road network	The user can update these values, if relevant, in the "Network Input" panel

3 Results

This chapter assesses the grid upgrade requirements at Auckland's bus depots and evaluates the local electricity networks ability to supply this additional capacity. The grid upgrades needed at each depot, alongside the associated cost, is calculated using the model presented in Chapter 2. The rest of this chapter is split into two sections as follows:

- **Baseline results** – Using the midpoint input values or Auckland Transport's best estimate of the average value for each input, these results present the best estimate of each depots peak power demand and grid infrastructure costs.
- **Sensitivity analysis results** – In response to the uncertainty in the input values, these results show the sensitivity of the model to changes in the model inputs. This section is designed to inform the model users where future efforts in data collection should be focused to ensure the outputs of the model are closely aligned with the real world.

3.1 Baseline Results

The baseline model inputs are summarised in Table 3. These values have been chosen because they are either: the average of all the values provided for the project or the best estimate as suggested by Auckland Transport or Auckland's bus operators.

Table 3 Model baseline inputs

Model Input	Input Value
Distance travelled per day (km)	Depot average
Charging Window (hr.)	11
Share of Buses in Use (%)[6]	81
Route Type (fuel consumption)	City Link
Rapid Charger Contingency (chargers per 100 buses in depot)	8
Time at final bus stop on route (minute)	4

The peak power demand of an electrified bus depot is dependent on many factors. The most important factors include: the number of buses, the bus duty cycle and the charging window. The differences in these factors lead to significant differences in peak power demand between depots, displayed in Figure 8 (dark blue), ranging from 0.8 to 4.2MW. The peak power demand at the depot is one of three factors that affect the grid upgrade costs alongside distances from primary substation and primary substation spare capacity. Figure 8 shows that the local primary substation spare capacity can change significantly between depots, with some forced to pay additional grid upgrade costs because of their location next to a primary substation with limited capacity (this will be a key factor considered when looking at which depots are best placed to transition to electric buses first in the next chapter). In some cases, no spare capacity is available at the nearest primary. The model has still selected these primaries for use because upgrading the primary is less expensive than running high voltage cabling to other primaries with more spare capacity further away.

[6] This factor accounts for the fact that not all buses in a depot are used on a daily basis.

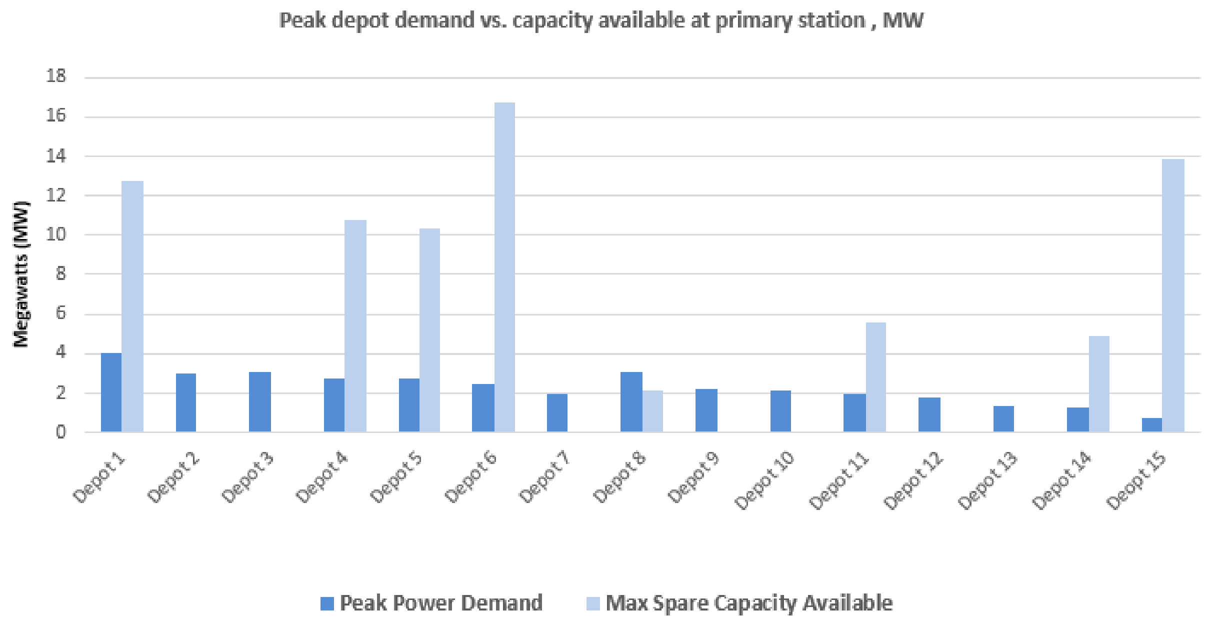
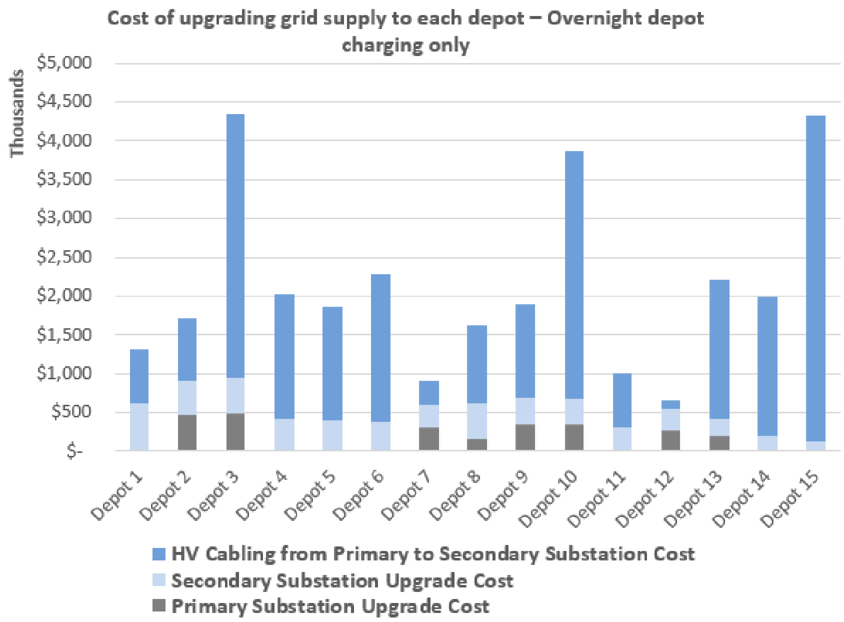


Figure 8 Depot peak power demand and spare capacity at the local primary substation

The peak power demand data displayed in Figure 8 leads to a grid infrastructure upgrade cost displayed in Figure 9. This cost data is broken down into the three main components of grid upgrade costs, these are:

- **Two common costs experienced at all depots**
  1. New dedicated secondary substation at the depot
  2. New high voltage cable from the depot to the primary substation
- **One depot-specific cost**
  3. Primary substation upgrade if the local primary has limited spare capacity

The total cost of upgrading the grid infrastructure at all the depots is estimated at **NZ$32 million.** Figure 9 shows that for many depots this cost is primarily made up of high voltage cabling costs which reflect the large distances between primaries in New Zealand. The second largest cost is the installation of new secondaries. These costs are directly proportional to the peak power demand of the depot and therefore follow the same trends between depots. The final and smallest cost is the primary substation upgrade costs. In most locations, the primaries have significant spare capacity. This means only 8 depots trigger a primary substation upgrade. 15 out of the 15 depots studied have a high enough peak power demand and a short enough charging window to trigger the inclusion of contingency rapid chargers. This suggests that these are likely to be needed at all depots and should be included in the planning from the beginning.



Total - NZ$ Millions	32.02
Number of primary station upgrades	8
Number of depots needing contingency	15

Figure 9 Depot grid upgrade costs (depot charging only)

The high voltage cabling costs are high for depots in Auckland because the depots are a long way from the primary substations (over 1km in most cases). For this work, where possible Vector has provided data for the nearest two primary substations to each depot. If primary substation upgrades are required, the cheapest option between the two primaries is dependent on both spare capacity and distance. Due to the high cost of cabling, it is worth noting that the primary substation with the largest spare capacity may not be the cheapest option if another primary is much closer, even if it needs upgrading. For some depots the 1st or 2nd primary substation is shared with another depot. In this case, the first depot to switch to electric will either use up the spare capacity, meaning the second depot must pay for upgrades, or trigger an upgrade, meaning the second depot avoids upgrades costs. How this works out, in reality, is dependent on the situation in each location. In terms of total costs, two depots sharing the same primary can increase/decrease costs as a primary substation upgrade will only be triggered once between the two depots. Whether this is an improvement depends on if the depots separately would trigger zero, one or two primary substation upgrades. In some regions where power cuts are a major concern it may be beneficial to connect depots up to different primaries to reduce the risk to the bus service. This kind of added detail is something that would be considered in a depot by depot detailed implementation study.

Like Figure 9, Figure 10 displays the cost of upgrading the grid infrastructure at the depot. However, Figure 10 shows the costs after opportunity charging has been used to avoid primary substation upgrades at the depot. Across all the depots, using opportunity charging has reduced the grid upgrades costs for the depots to **NZ$16 million** (additional costs for installing the opportunity chargers will be experienced under this scenario, and these may outweigh the depot grid cost reductions, but these costs are not modelled in this work). In total eight depots have triggered the use of opportunity charging in seven of these depots the primary substation upgrade needs have been as large as the peak power demand (there was no spare capacity on the primary). In these cases, the model meets 100% of the charging demand using opportunity chargers (in practice, some depot chargers might always be required for battery balancing). This is achieved using opportunity chargers smaller than 300kW which are available on the market today. This suggests that some depots could make use of a charging strategy that relies almost entirely on opportunity charging (systems using this setup such as the TOSA bus in Geneva have been developed so this is an option that could be explored by Auckland's bus operators). It is also worth noting that other depots, beyond those selected by the model, could benefit from opportunity charging. For example, depots such as Depot 15 which are a long way away from the nearest primary may benefit from an opportunity charging strategy that to a large extent avoids depot charging. Choices such as this that could help to optimise the cost of the charging strategy will be a key outcome of the detailed analysis that is required for each depot before implementation of an electric bus strategy is realised.

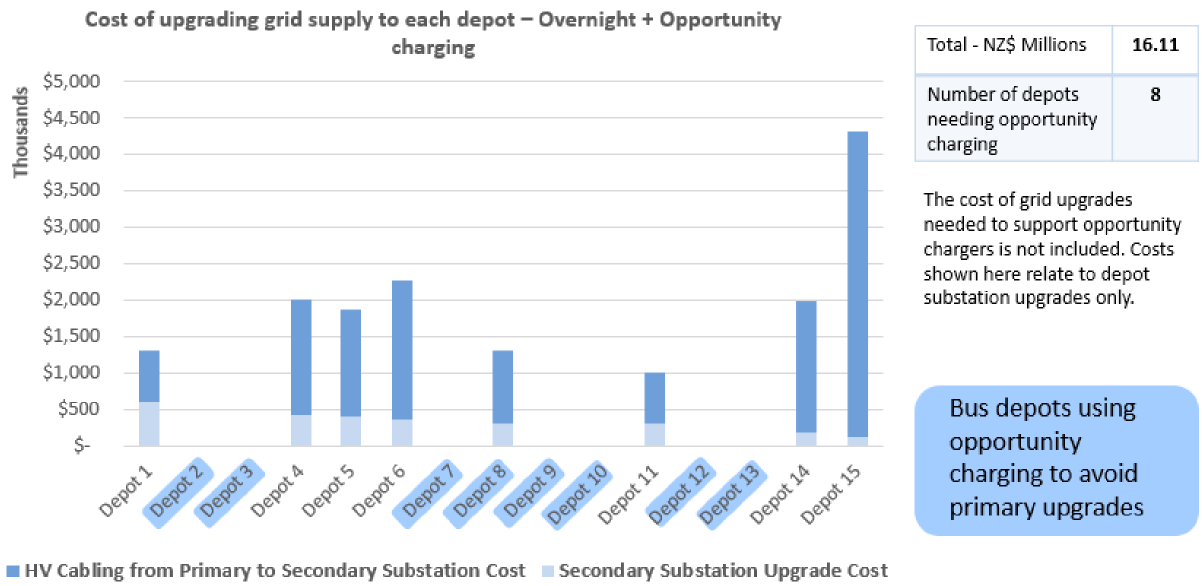


Figure 10 Depot grid upgrade costs (depot and opportunity charging)[7]

3.2 Sensitivity Analysis

This analysis is designed to help the user understand the sensitivity of the depot grid upgrade costs to different model inputs. This should help the user focus their efforts when collecting data to use for the detailed bus electrification plan for each depot. Table 4 displays the inputs used for the sensitivity analysis (a complete description of the input values chosen is given in Table 7 in the appendix). For each input, a worst and best-case scenario ("worst" is the highest grid costs and "best" the lowest grid costs) has been developed based on the range of data values provided by Auckland Transport.

Table 4 Sensitivity modelling inputs

Model Input	Worst (% change)	Baseline	Best (% change)
Distance travelled per day - Mileage Scenario	Maximum (+20%)	Average	Minimum (-20%)
Charging Window (hours)	3 (-73%)	11	18 (+64%)
Share of buses in use (%)	91% (+12%)	81%	71% (-12%)
Fuel Consumption (kWh/km)	2.97 (+45%)	2.05	1.13 (-45%)
Number of contingency chargers (per 100 buses)	12 (+50%)	8	4 (-50%)

Figure 11 compares the sensitivity of the model for a range of input values for both the overnight depot charging and the depot charging plus opportunity charging scenarios. For all inputs the addition of opportunity charging makes the depot costs less sensitive to changes in depot/vehicle operation. This is to be expected, as the size and cost of the opportunity chargers increases/decreases to cover the changes in depot peak power demand caused by the sensitivity analysis.

Even when correcting for the fact there is a larger percentage change in the charging window than any other input, the model is still most sensitive to charging window. This demonstrates the importance of collecting accurate data on the charging window at each depot. The next most important inputs to collect

[7] This plot displays the depot grid upgrade costs if depot and opportunity charging are deployed. It does not include the cost of grid upgrades needed to install the opportunity chargers

accurately are vehicle fuel consumption, distance travelled per day and the share of the buses within a depot in use on a given day, which all affect the cost by a similar amount when they are shifted by an equal percentage. The least important of the inputs is the number of rapid contingency chargers. This is because there are relatively few rapid chargers compared to the total number of buses being charged.

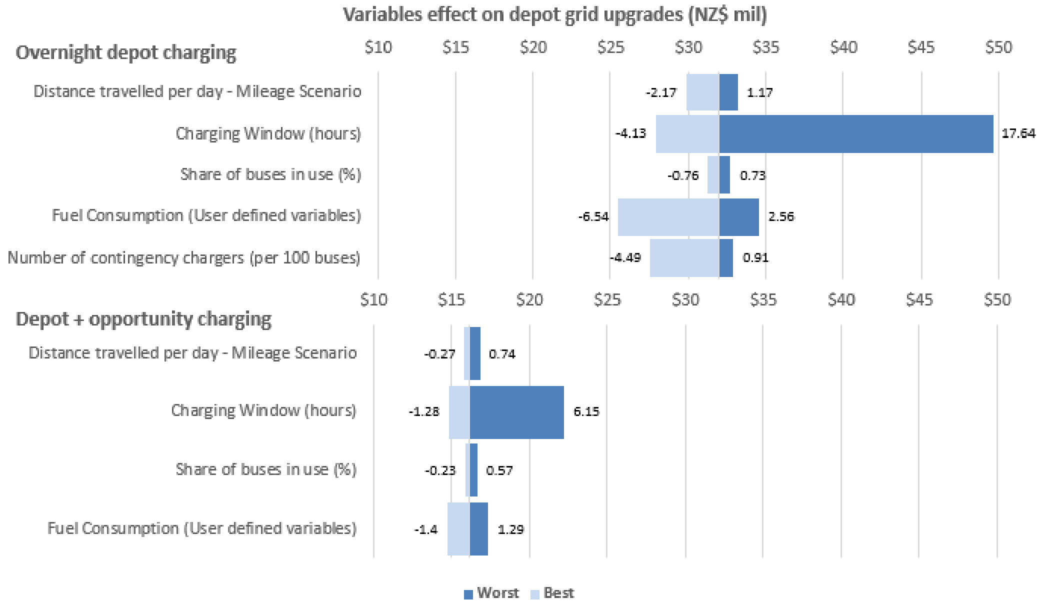


Figure 11 Sensitivity analysis of total depot grid upgrade costs across the key model inputs

As the grid upgrade cost is so sensitive to the charging window, Figure 12 displays the cost versus charging window trends in more detail. Costs start very high at the lowest charging windows because high power chargers are needed to charge the vehicles in the small charging window. To achieve this, depots would need to make use of 100kW depot chargers for every bus. This is possible as products that match these requirements are available, but these chargers are relatively expensive[8] so alongside the high grid upgrade costs at the depot the whole project would be extremely expensive. The grid costs at the low charging window end of the plot are also increased by the need for rapid contingency chargers, which are needed by very time constrained depots as they lack the charging flexibility to meet unplanned changes in bus use.

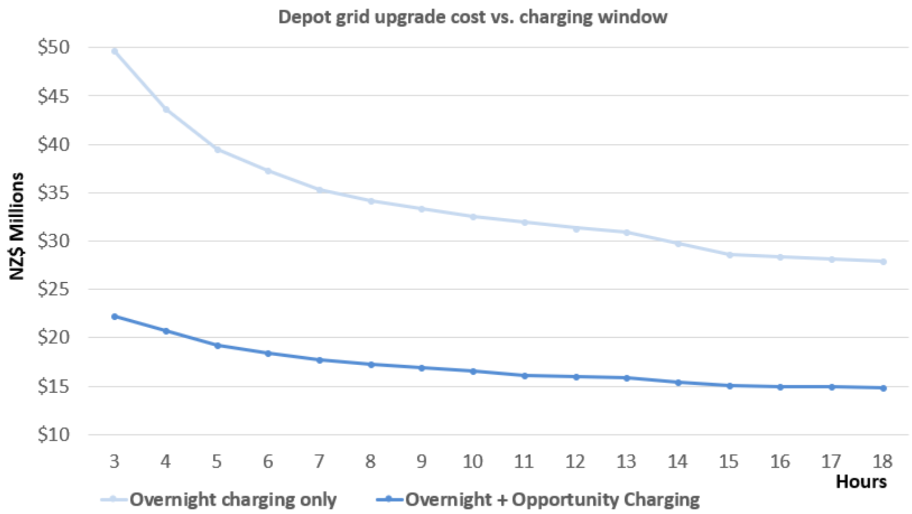


Figure 12 Sensitivity of the model to the charging window (all other inputs set to baseline)

[8] For most buses to charge at around 100kW the required DC charger is relatively expensive because it needs an internal rectifier to convert AC to DC. This issue has been overcome by e.g. BYD who install two 40kW AC sockets on the buses they produce with ADL. This reduces the cost of the charge points but also increases the amount of equipment needed on-board the bus.

4 Interpretation of the results and recommendations

Based on the results and discussion presented in the previous chapter, this chapter will provide further recommendations about the actual introduction of electric buses. This discussion will cover:

1. A phasing plan for the conversion of Auckland's 15 bus depots over to electric buses
2. The networks' resilience to the switch to electric buses and the effect on other fleets wishing to convert to electric
3. Mitigation strategies that could be employed by depots to limit their peak power demand
4. Recommended next steps for Auckland Transport in their efforts to support an electric bus transition

4.1 Phasing of the electrification of depots

Auckland currently has two targets relating to the introduction of zero-emission buses. These are:

- All new buses bought into the fleet should be zero-emission by 2025
- All buses should be zero-emission by 2040

To minimise the overall infrastructure costs of switching the fleet to electric buses will require careful planning of which depots and routes are electrified first. One important difference between updating a diesel bus fleet and introducing new electric buses is that it can be very challenging and costly to introduce electric buses in phases within a depot as old buses are retired. This is because the grid infrastructure must either be oversized to accommodate a depot full of electric buses when only a few have been introduced or the grid infrastructure must be updated multiple times as the proportion of electric buses within the fleet increases. Both options result in additional expense, especially the second option which could lead to a 2-4 times increase in the total grid infrastructure costs per depot, but the first option also increases costs because the bus operator will have to pay a high capacity charge as part of their electricity bill when they are only using a small proportion of that capacity.

To help overcome this issue, the depots should be converted to electric buses in phases. Each operator should concentrate all their new electric buses in one depot, while moving middle age buses out of that depot to other depots to replace any buses retired. This practice may increase costs for Auckland Transport from operators claiming for out of service running but as discussed in the previous paragraph this practice will reduce total electrification costs so significantly for bus operators that they are unlikely to accept the costs if the introduction of electric buses in each depot is staggered. This process will be much easier for larger bus operators or operators with multiple depots. Operators not meeting these criteria may, therefore, need additional support to achieve the transition.

The phasing of Auckland's bus depots over to electric buses is summarised in Table 5. The four phases suggested are:

1. **Testing (2 depots)** – Depots that are well suited to early electric bus introduction and testing have been selected based on four criteria. These are: a large operator able to manage the introduction, enough spare capacity at the local primary, short distance to the local primary and low overall depot conversion costs.
2. **Phase 1 (2 depots)** – Depots are selected for phase 1 introduction based on three criteria. These are: Low number of buses in depot to minimise vehicle/charger costs, low overall grid upgrade costs and run by operators with at least two depots to allow diesel bus switching.
3. **Phase 2 (8 depots)** – Depots are placed in phase 2 if they do not meet the phase 1 criteria and their overall depot grid upgrade costs are less than NZ$2.5 million.
4. **Phase 3 (3 depots)** – Phase 3 includes the most expensive depots in terms of grid upgrade costs. It is sensible to leave the most expensive depots to last as depot/grid conditions will change over time meaning these depot conversions may be cheaper in the future.

Table 5 Electric bus phasing schedule

Operator	Depot (anonymised)	Number of Buses	Distance to Primary (km)	Grid Upgrade Cost (NZ$ million)	EV Introduction Phase
Operator 1	Depot 1	152	0.7	1.3	2
Operator 2	Depot 2	111	0.8	1.7	2
	Depot 12	66	0.1	0.65	1 (Testing)
Operator 3	Depot 3	113	3.4	4.4	3
	Depot 5	98	1.5	1.9	2
	Depot 6	91	1.9	2.3	2
	Depot 9	81	1.2	1.9	2
	Depot 11	71	0.7	1.0	1 (Testing)
	Depot 13	47	1.8	2.2	1
	Depot 14	46	1.8	2.0	1
Operator 4	Depot 4	102	1.6	2.0	2
	Depot 15	27	4.2	4.3	3
Operator 5	Depot 7	86	0.3	0.91	2
Operator 6	Depot 8	85	1.0	1.6	2
Operator 7	Depot 10	81	3.2	3.9	3

4.2 Impact of electric buses on the network resilience

The introduction of electric bus fleets will have a significant effect on the local electricity grid. The ability of the grid to handle this new demand and still provide for other users is an important concern. As all the bus depots in the Auckland area would have a power demand larger than their local secondary, if they were converted to electric, the introduction of electric buses will have no effect on other users at the secondary level. However, at the primary level the introduction of electric bus fleets will reduce spare capacity in some areas and increase spare capacity in others. This means that for future fleets looking to move to electric vehicles the prior switch to electric buses in their area could have a positive or a negative effect on the local networks ability to supply power for charging. With the current spare capacity at a primary level, 8 depots will trigger a primary substation upgrade. For fleets close to these depots this means they can convert to electric fleets without having to pay for primary substation upgrades. For the other 7 depots, the introduction of the electric bus fleets has reduced the primary spare capacity. However, there is still MW of spare capacity available at these primaries meaning other fleets in the area will also be able to switch to electric vehicles without paying for primary substation upgrades.

Figure 13 shows the peak power demand of all the bus depots in Auckland if they were converted to electric, and what proportion of Vector's peak capacity this equates to. This demonstrates that, while the electricity demand of electric bus depots is significant, and, while the effect of this demand on the network is exacerbated by the geographical concentration of demand, in terms of Vector's overall peak capacity the bus depots are a relatively small demand. This suggests that the introduction of the electric buses will cause localised problems and grid upgrades, but that the higher levels of the distribution and transmission networks are likely to be unaffected.

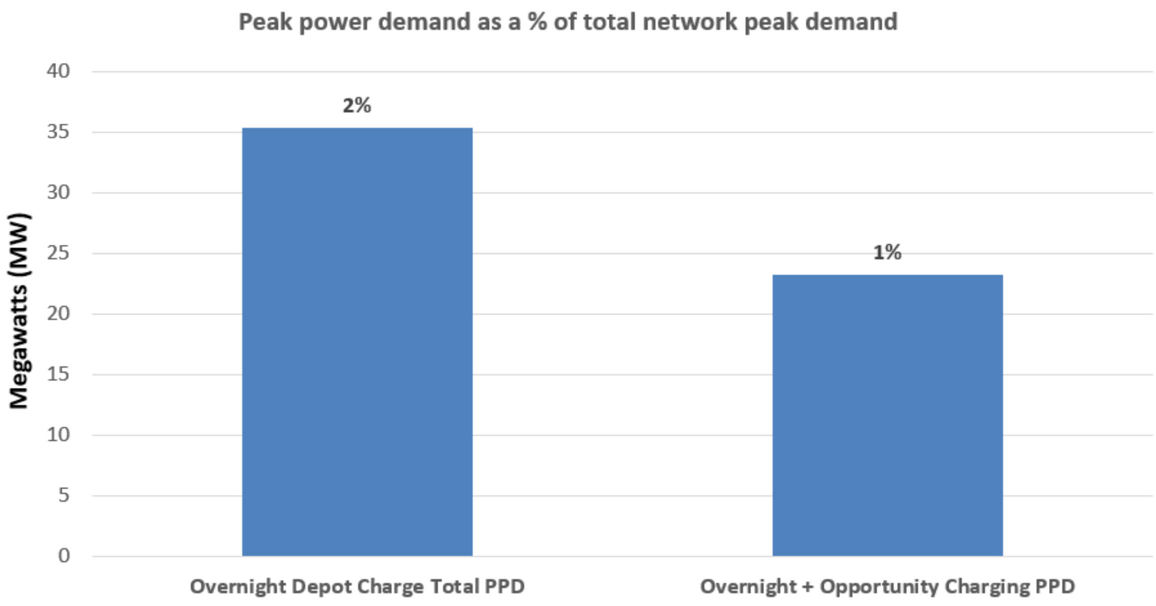


Figure 13 Bus charging demand as a percentage of Vector's peak power capability

While the electrification of Auckland's bus depots will have a significant effect on the local electricity grid, this effect is expected to be much smaller than the effects caused by electric car uptake. The New Zealand government currently has a target of 64,000 electric cars on the road by 2021 (a target they are on track to meet). As Auckland has New Zealand's highest density of electric cars, this target could mean that Auckland has over 30,000 electric cars on the road in 2021. Each electric car is expected to predominantly charge at home. Common home chargers are 2.4-3 or 7kW, while the average house in Auckland has a load of 2.5kW. This means each electric car will significantly increase each homes power demand resulting in significant grid upgrades at all levels of the grid (initial electric car uptake is expected to cluster, whether these clusters are geographically close to the bus depots is something that Vector and Auckland Transport should attempt to better understand in future studies). Vector has estimated that if 10% of Auckland's households have an electric car (equivalent to 50,000 electric cars) and they charge at 2.4kW or 7kW this will require grid upgrades of the value of NZ$ 20 or NZ$ 100 million respectively. As these levels of electric car uptake could be achieved in the very early 2020s and further uptake of electric cars is expected throughout the 2020s and 2030s it is clear that the total grid upgrades caused by electric cars by 2040, when the electrification of the depots will be complete, will be significantly higher than those caused by bus electrification. In fact, in Vector's most ambitious electric car uptake scenario (40% of Auckland's homes have an electric car) the grid upgrade costs are up to 20 times higher than those caused by bus electrification (see Figure 14 in the appendix for statistics and sources).

Overall this example demonstrates that the electrification of the bus depots is very unlikely to cause grid problems for other fleets wishing to move to electric vehicles because the whole grid will be undergoing significant upgrades to support electric cars. This is also why depots that are very expensive to convert to electric buses should be upgraded in Phase 3, as the grid will look very different in the future and costs for these depots could well be lower under these conditions.

4.3 Mitigation strategies

As presented in the results section the cost of upgrading the grid infrastructure around an electric bus depot can be a significant proportion of the total cost of transitioning to electric bus fleets. A number of mitigation strategies exist to improve the operator's experience of charging buses and to reduce the overall cost of the transition. Mitigation strategies commonly in use around the world include:

- **Smart charge management** – this can significantly reduce the peak power demand at the depot by managing the charging power to each bus based on: charging window, bus battery state of charge, bus duty cycle the next day, etc.
- **Shifting charging** – shifting the charging time or location through the use of: opportunity, flash or day depot charging, which can significantly reduce the chance that a primary substation upgrade is required.
- **Increased flexibility** – daytime charging and buses with larger batteries can provide greater flexibility for the bus operator in terms of charging times and bus routes.
- **Timed tariffs** – these tariff agreements allow a bus depot to have a different capacity allowance during the day and night. This reduces the capacity charges the depot has to pay and offers the opportunity to avoid primary substation upgrades by agreeing to only demand high powers during the night when other local demand is low.
- **Energy storage on site** – On-site energy storage that can be charged slowly during the day can be used to meet peaks in power demand throughout the night.
- **On-site/Local renewable energy generation** – local renewables that can be used directly or through on-site energy storage to charge vehicles without first passing through the electricity grid can help to avoid grid upgrade costs.

The fundamental role of **smart charge management** is to balance the charging across the depot either by charging buses slowly or by charging buses in shifts to reduce peak power demand by making use of the full charging window. This aspect of smart charging has already been included in the model because it has great value to operators and we, therefore, expect all bus operators to use it. However, beyond this core function of smart charge management has other features that can reduce peak power demand. These include:

1. Smart chargers can delay the start of charging from the time when the bus is plugged in. This makes it possible for operators to reduce costs through timed tariffs as the management system ensures the buses are not charged outside of the reduced cost tariff period.
2. Smart charge management systems can be programmed with the energy demands of the next day's routes. This allows the system to charge some buses to less than 100% state of charge if this is not required the next day.
3. Most bus depots in the Auckland region have an excess of buses, meaning not all buses at a depot are in use every day. Smart charge management could charge these buses at the lowest cost, outside of the nighttime charging window. These buses could then be used in the place of some of the depleted buses. The depleted buses which are not required for use the next day then do not need to be charged overnight and will not add to the depot peak power demand.

Shifting charging either temporally or spatially away from night depot charging can help to reduce peak power demand. The charging solution needs to be carefully planned as shifting charging bus stops can increase the total cost if the grid supply to these locations is constrained. The two best opportunities for shifting charging are:

- temporal shifting: using charge management and the excess of buses to charge during the day
- spatial shifting: opportunity or flash charging along a route.

Opportunity charging (charging at or near the last bus stop on a route) and flash charging (charging at bus stops along a route) have become increasingly popular charging technologies in Europe. While opportunity and flash chargers are much more expensive than depot chargers, they can help to avoid grid upgrades. This is achieved both at the depot, by reducing the average and peak power demand over the night, and potentially at the opportunity/flash charger, where on-site energy storage can be effectively used to modulate the long waiting times/short burst of power charging pattern of opportunity chargers into a low constant power demand from the grid which requires a much smaller grid connection (Opportunity chargers are currently on the market with a 50kW power demand from the grid and a 150-600kW power supply to the bus (charging is from 20s to several minutes)).

Timed tariff agreements can be made that prevent users from demanding more power than set limits at certain times. These agreements can be particularly beneficial as they can help to avoid primary substation upgrades. This type of arrangement can work very well for electric bus depots who consume most of their power at night when general demand is low. For example, Waterloo bus depot in London has converted all its buses to electric. They have a 2.5MW grid connection but also has a timed connection that only allows them to use up to 0.5MW during the day. Through this agreement, the operator has avoided paying for primary substation upgrades that would have been necessary if they had needed a 2.5MW connection day and night. It is not clear if Vector is able to offer this service.

Trials of **on-site energy storage** at electric heavy-duty vehicles (trucks and buses) depots are currently being undertaken. This solution offers the opportunity to charge up energy storage devices slowly during the day. This energy storage can then be used through the night to reduce the average power demand throughout the night and to meet peaks in demand thus reducing the peak power demand down to the average power demand. As these solutions are currently at the trial stage it is not yet clear if this solution will be a cost-optimal solution. However, this solution may be preferred by bus operators as it transfers the costs from an asset owned by the DNO (new substations) to an asset owned by the bus operator (new energy storage device). This provides the bus operator with much more flexibility to change depot location or change the number of vehicles operating from a depot without losing the asset as it can be sold or moved to a new site. This solution is also expected to become much more cost-effective over time as battery prices fall and as this solution can make use of second life batteries which will become increasingly available, while grid costs will remain unchanged. On-site battery storage is currently being trailed by UPS at one of their depots in London. The battery system provided by gridtogo will be used to mitigate grid upgrade costs, can be used to derive revenue by providing grid services and acts as a backup if grid power is disrupted to ensure the fleet continues to operate.

Alongside on-site energy storage, **on-site/local energy generation** from renewables can also provide a solution to grid upgrade costs by generating and storing electricity without the use of the electricity grid. Solutions using this concept have not yet been trialled and so the cost-effectiveness is not yet known. However, as with energy storage, the price of these solutions will fall significantly over the coming years and so this solution should be reviewed at an early stage in the electric depot planning.

4.4 Next steps for the refinement of the cost analysis

Before bus depots commit to introducing electric buses a detailed assessment of the total costs at each depot is required. This more detailed analysis should be scoped to include all costs including: vehicle, depot grid upgrades (specifically focusing on HV cabling costs which are currently uncertain as the cabling route is unknown), depot chargers, opportunity charger grid upgrades, opportunity chargers and mitigation strategy costs. To achieve this analysis far more detailed information regarding the operation profile of buses at each depot will be required. This work has highlighted several parameters that need to be understood in greater detail to facilitate this more detailed analysis, specifically: charging window, distance driven and vehicle efficiency. A more detailed analysis would also need to understand the most challenging daily operation profile for each depot to size the bus batteries and detailed information on the number of buses completing each route and the route location to assess the true potential of opportunity charging. This more detailed analysis should cover the full implementation of the electric buses including: current routing and whether this will have to change due to the range of the electric buses or because some routes must have common end points to share opportunity charging, selecting specific vehicles and chargers from the wide range available on the market, and vehicle options under current Vehicle Dimensions And Mass (VDAM) rules that may have to be updated to allow the use of the best available electric bus technology.

Before proceeding with electric bus trials, workshops with the bus operators would also help to avoid later problems. These workshops should focus on informing bus operators about the process of switching to electric buses and finding out how each operators situation could help/hinder them in switching to electric buses. For example, as has been highlighted earlier in this section, bus operators with a single depot will struggle to introduce electric buses in one go but will be faced by higher grid costs if they introduce electric buses in phases. Other problems that have been faced by European bus operators switching to electric buses include, for example, lack of space within the depot to house a new secondary substation and the bus chargers. These types of problems often only become apparent once a system is in place but working closely with the bus operators to ensure they fully understand the process should bring these problems to light early when they can be factored into the detailed design.

5 Appendix

5.1 Bus depot list and maps

Table 6 Bus depots in scope of the study. Source: Auckland Transport

Depot Number	Number of Buses
1	152
2	111
3	113
4	102
5	98
6	91
7	86
8	85
9	81
10	81
11	71
12	66
13	47
14	46
15	27

5.2 Sensitivity analysis inputs

Table 7 Sensitivity modelling inputs

Model Input	Worst	Baseline	Best	Comments
Distance travelled per day - Mileage Scenario	Maximum	Average	Minimum	The Average is calculated as the total annual kms per vehicle divided by 365 days. The Maximum and Minimum are 20% more and less than this number
Charging Window (hours)	3	11	18	Minimum 3 hours, Maximum 18 hours. Estimated average time of buses in depot (based upon average/kms day) (Source: Auckland Transport, e-mail 06/04/2018)
Share of buses in use (%)	91%	81%	71%	Baseline = 81%, based on 1100/1350 buses [Source data: Auckland Transport, email 05/04/2018]
Fuel Consumption (kWh/km)	2.97	2.05	1.13	Baseline of 2.05 kWh/km is the average fuel consumption of City Link and Inner Link's routes used in the model. Best of 1.13 kWh/km is the average fuel consumption of the route 973 used in the model. Worst of 2.97 kWh/km is calculated as the same percentage difference between Baseline and Worst
Number of contingency chargers (per 100 buses)	12	8	4	Based upon review of European electric bus depots

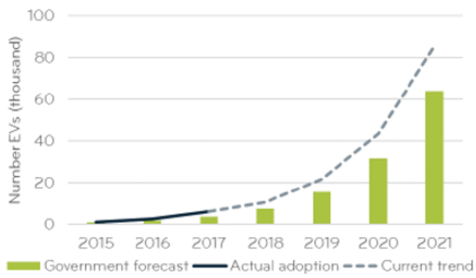
5.3 Summary for electric vehicles statistics

Total EV Registration in Auckland and New Zealand

	AUCKLAND	NEW ZEALAND
Light plug-in hybrid	965	1,900
Light pure electric	2,528	5,252
Total	**3,493**	**7,152**

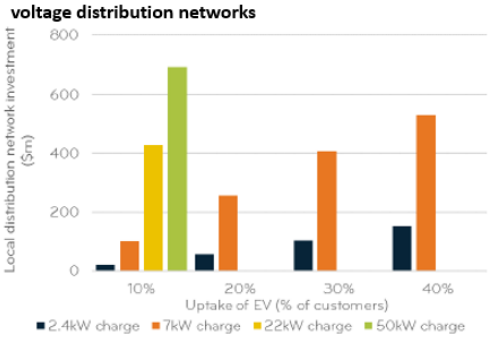
Source: New Zealand Ministry of Transport vehicle fleet statistics

Vector Projection of New Zealand's EV fleet



Source: International Energy Agency, Global EV Outlook; Vector – EV Network Integration Green Paper

Investment impact of the uptake of EV on low-voltage distribution networks



Vector displays the projected investment needed into their local distribution network based upon the take up of EV's and types of chargers

Source: Vector – EV Network Integration Green Paper

Figure 14 New Zealand and Auckland electric car statistics