Electric Vehicles

Impacts on New Zealand's Electricity System

Technical Report

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CONTENTS

Executive Summary

Electric Vehicle Availability

A number of vehicle manufacturers have commenced production of battery (BEV) and plug in hybrid (PHEV) electric vehicles on a relatively small scale. Whilst these vehicles have limited appeal in the present mass markets compared to conventional internal combustion (ICE) or hybrid (HEV) vehicles because of high costs and performance limitations, anticipated improvements in battery technology and costs of manufacture indicate that electric vehicles will emerge as genuine contenders as high energy efficiency, low emissions alternatives to other road transport technologies:

- The key constraint to electric vehicles is the high cost and low energy density of the batteries. Batteries typically comprise over half the cost of BEV models and weight and cost compromises typically limit their range to 160 km. Similarly, PHEV "electric only" operation is generally limited to 10 to 60 km.

- Battery performance is continually improving and, with the focus now on lithium-ion and potentially lithium sulphur technologies, the barriers imposed by capital cost and limited range are expected to erode with time. The time when electric vehicles can be fully competitive in the mass markets is open to speculation but most studies reviewed anticipate costs of electric and conventional vehicles to converge in about 2030, when the former will assume a significant share of the new vehicle market.

- Initially PHEVs are expected to be the favoured electric vehicle technology but BEVs are expected to predominate as battery performance and costs improve, as they are a simpler and cheaper technology.

- Volume of sales of electric vehicles into the New Zealand market will be the primary determinant of the electricity requirement to power them. Technical factors, such as vehicle energy efficiency and battery charging efficiency, have limited scope for improvement over current benchmarks, even during the 30 year period of this study. Given the uncertainties regarding their commercialisation, electricity consumption at different levels of uptake of electric vehicles have been investigated, ranging from 50% to 80% of light vehicles entering the New Zealand fleet in 2040.

Battery Charging

The ability to charge batteries outside periods of peak electricity demand will significantly reduce the electricity generating capacity required to service the electric vehicle market. Technology is available to charge vehicles at home or in public places and is unlikely to impose any constraint on electric vehicle market development:

- Private vehicles are used on average 39 kilometres per day and, with a median distance travelled of 23.2 km per day, a disproportionate amount of total vehicle kilometres travelled (VKT) can be apportioned to a relatively small number of vehicles.

- Batteries can be charged at home at an input of 2kW with no modification to household single phase wiring, and up to 5kW with the installation of a heavy-duty circuit from the household switchboard. At 5 kW, electricity to travel the average vehicle distance travelled would be delivered in about 1.5 hours. Above this, three-phase supply will be desirable and "fast fill" technology is being developed for commercial and public application with battery inputs in the order of 78 kW.

- More than 90% of vehicles are parked between 10 pm to 6 am weekdays (80% from 6 pm to 10 pm) at home, mainly on residents' property, indicating a large number of vehicles can be charged overnight in a safe environment whilst demand for other electricity uses is relatively low.

- Not all electricity demand from electric vehicles can be delivered overnight. In some cases cars will not be parked in secure locations and household charging rates and battery capacity may not be sufficient to provide electricity for the following day's travel for high use vehicles. Whilst relevant at present, the battery capacity limitations will become insignificant should battery technology improve as anticipated. Charging rate constraints would be significant with 2 kW chargers but considerably less so at 5 kW. It is estimated that up to 85% of daily electricity requirements could be delivered overnight at the higher charging rate once the battery capacity limitations are overcome.

- Any shortfall between total electricity demand and charging at night must be undertaken during the daytime. There are several opportunities for this: 40% of vehicles are parked at home at any time during week days and about 30% at work as well as public charging facilities including "fast fill" technology under development.

- There are a number of regimes that could be applied to EV charging and it is important that the complexity and cost of the regime is appropriate for the problem being resolved. The timing of various approaches such as smart chargers, ripple control, two-way communications and smart meters with real time pricing will be dependent on the uptake of EV's and the pace at which smart network initiatives become economic in NZ. The disaggregated nature of the NZ electricity sector creates challenges (that must be addressed) to implementing coordinated demand side management and smart EV solutions.

Electricity Supply

The impact of electric vehicle charging on the electricity generation system over the next thirty years is likely to be relatively small given that the electricity demand from vehicles is estimated to be no more than 8% of total demand by 2039 for the most optimistic scenario of electric vehicle uptake investigated. Additional generating capacity required can be reduced significantly by charging electric vehicles during off peak hours, particularly when parked at private residences overnight. This has been illustrated by the 80% Uptake Scenario, a rapid uptake of electric vehicles:

- Undertaking 85% of battery charging during shoulder and off-peak hours and no charging during the 35 annual "super peak" hours results in significant savings in generation system costs compared to uniformly spreading the charging load - a 19% saving for this scenario.

- Additional non-schedulable generation is made economic by the use of off-peak and shoulder hour battery charging. This results in a significant amount of additional wind capacity being added to the system, with smaller amounts of hydro, marine and biomass.

- By displacing some fossil fuelled peaking plant due to additional non-schedulable renewables becoming economic, total CO_2 emissions from the power system are reduced, despite the increased load.

- By 2025, over 390,000 electric vehicles are in use under this scenario, but total additional generation capacity has not exceeded 180 MW.

- Assuming 15% of charging occurs randomly, including over the super peak hours, has no significant effect on the average cost of generation, but might have some effects in transmission and distribution systems.

- Electric vehicle charging is a load that can be interrupted and offers potential to reduce reserve capacity requirements to meet peaks and to provide the required reserve margin. The traditional form of load control in New Zealand has been the ripple control system, still used by some lines companies to reduce peak loads. Multiple ripple control channels could be used to progressively switch chargers as necessary. Ripple

control is inherently a unidirectional system, so some form of "smart" bidirectional communications would be of benefit eventually, allowing individual premises and chargers to report on current state of charge.

Distribution Impacts

Local electricity distribution networks supplying to residential neighbourhoods are likely to be impacted by the simultaneous operation of battery chargers if there is widespread use of electric vehicles. A limited analysis of harmonic voltage effects and voltage drop for typical load low-density overhead and high-density underground residential feeders, supplying 75 homes respectively[1], indicates:

- That harmonic distortion would exceed current standards if more than 40% of households were simultaneously operating chargers at the rated 5kW output.

- The impact could worsen rapidly if the chargers have lower harmonic diversity or exceed the IEC 61000-3-2 Class A standard assumed in the study.

- Higher power rated EV chargers will have a near proportionate effect on harmonic levels. For example, the voltage THD for 5kW chargers is likely to be approximately 67% higher than for 3kW chargers.

- There is a range of additional power quality issues that are likely to occur with high levels of chargers operating that require further analysis that were outside the scope of this report.

Carbon Dioxide Reduction

One of the primary benefits of utilising electric vehicles is the associated reduction in carbon dioxide emissions due to the reduced consumption of hydrocarbon fuels by conventional vehicles displaced by electric vehicles. The reduction of these tailpipe emissions may be offset by increased consumption of hydrocarbon fuels during the generation of electricity to supply the electric vehicles. This analysis indicates there may be a significant reduction in total carbon dioxide emissions:

- In the 80% Uptake Scenario there is a reduction in total electricity generation system emissions of 0.68% if charging times are controlled. This somewhat counter-intuitive result is achieved by the flattening of the power system load curve, which favours the construction of renewable technologies in place of fossil fuel plants. However, the differences in emissions are small and depend on the level of control. With uncontrolled charging, across all hours of the day, an increase in emissions of 0.32% occurs over the 30 year study period.

- Reduction in tailpipe emissions will depend on the uptake of electric vehicles and the type of vehicles displaced by electric vehicles. The displacement of HEV or diesel vehicles will result in a smaller reduction in emissions than the displacement of conventional petrol vehicles of similar size and usage. The scale of reductions range from over 3 million tonnes of CO_2 per annum in 2040 for the 80% Uptake Scenarios to 1.5 million tonnes for the lowest scenario investigated. These reductions could be diminished by about 0.5 million tonnes if the electric vehicles were to displace HEVs rather than conventional petrol vehicles.

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[1] Operation conditions assumed to be each house had a normal load of 2 kW (PF=0.97), approximating winter early morning (1 – 4 am) loading, as an optimal time for residential battery re-charging.

- Overall the tailpipe emissions reductions are significantly greater than the changes in carbon dioxide emissions from electricity generation. Over the 30 year study period, the cumulative tailpipe emissions reduction in the 80% Uptake Scenario will be in the order of 30 million tonnes compared to a reduction of less than one million tonnes in the power system.

1 Introduction

Electric vehicles (EVs) have emerged as genuine contenders as high-energy efficiency, low emissions alternatives to conventional internal combustion vehicles, which have totally dominated road transport for the last century. In the longer term they will compete with such technologies as biofuels, hydrogen and fuel cells in the diversification away from oil fuels and the continuing objective of reducing environmental impacts, in particular the reduction of carbon dioxide emissions from the transport sector, to date a largely intractable problem in the drive to reduce greenhouse gas emissions.

Compared to the other alternative transport fuels options, electricity already has an established supply system in New Zealand with a fully integrated system of generation, transmission and distribution. Supplying electricity to vehicles will place additional demands on each of these components but not necessarily in proportion to the additional energy consumed, particularly as much of the electric vehicle battery charging can be undertaken during periods of relatively low electricity demand and battery charging is potentially a controllable load. The objective of this study is to investigate the impacts of electric vehicles on electricity supply and identify when these impacts might become significant.

CAENZ has a long-running interest in the supply of energy to the New Zealand economy and the development and resilience of the county's infrastructure. Electric vehicles will impact on both these interests. As yet no independent study of the supply-side issues relating to electric vehicles has been made public. This report is a first step in providing this information and, as such, is not intended to promote electric vehicles but rather to provide some substance to the debate regarding future transport fuels options.

The paucity of public information is partly due to the small number of electric vehicles in operation today and their anticipated slow uptake as they gradually become economically competitive with conventional vehicles. It is commonly held that electricity supply will not be a constraint to the use of electric vehicles in that the gradual uptake of electric vehicles over the next ten years at least will allow the electricity supply industry to adapt in turn. This report does not dispute this view but sets out to identify where this adaptation will take place and what issues and opportunities will arise during the process. It does not address the comparative economics of operating electric and conventional vehicles but uses different electric vehicle uptake scenarios based on other studies to place electricity demand from transport into the context of the otherwise expanding electricity market.

1.1 Status of Electric Vehicle Technology

Electric vehicle technology is not new in principle and has been developing on a number of fronts:

- Battery-powered vehicles (BEVs) have been available for some time and used commercially in specialist applications such as small urban delivery vehicles and forklifts where low noise and emissions are important features. Compared to conventional road vehicles and other electric vehicles described below, BEVs are mechanically very simple as most electric motors, unlike internal combustion engines, deliver full torque from rest over a wide engine speed range, allowing them to be controlled without the need for multiple gears. However, their performance is constrained by the cost, weight and comparatively low energy density of the lead-acid and nickel-metal hydride batteries used to drive the electric motors and they have had very limited appeal to the wider motoring public. The Californian zero emissions mandate in the 1990s stimulated interest in the commercialization of EVs but resulted in only a small number of sales for similar reasons. "Range anxiety", or the limited range of electric vehicles compared to conventional vehicles arising from the low energy density of the batteries, is a major constraint to their commercialisation.

- Hybrid electric vehicles (HEVs) have been successfully commercialized in the 2000s by a number of vehicle manufacturers. These vehicles integrate combinations of internal combustion engine, generator, storage battery and electric motor to optimize engine size and operation, thereby significantly increasing energy efficiency. The operation of the electric motor complements that of the internal combustion engine with no specific "electricity only" operation. Batteries used in HEVs are relatively small compared to those in electric vehicles[2] and nickel-metal hydride battery technology is generally used. HEVs are powered by petrol or diesel only as all the electricity used to drive the electric motor is generated by the internal combustion engine. Consequently HEVs are not generally classified as electric vehicles but as highly efficient conventional petrol or diesel vehicles.

- Battery technology has been a major constraint in developing marketable EVs. Batteries have low energy density compared to petrol and diesel, are very expensive and have limited capability in terms of power delivery and number of recharge cycles during their useful life. However, there have been significant improvements in recent years as manufacturers have shifted from traditional lead-acid batteries to nickel-metal hydride used in hybrids and latterly to lithium-ion batteries which are now the future focus for both HEVs and electric vehicles. Lithium-ion batteries have superior power and recharging capabilities and, according to most sources, superior energy density than their nickel-metal hydride counterparts. There is considerable optimism that their cost and energy density can be significantly improved in the future. Lithium-ion is a generic term but the batteries usually have a carbon anode and have a number of cathode variants, including cobalt dioxide, nickel-cobalt-manganese, manganese oxide and iron phosphate, each providing a different mix of cost, durability, performance and safety. The cobalt dioxide variant is commonly used in cellphone and portable computer batteries.

- A number of vehicle manufacturers are introducing plug-in hybrid electric vehicles (PHEVs). These are variants of HEVs but with a larger battery which can be recharged from an external electricity source, effectively making them bi-fuel vehicles, fuelled on both petrol and electricity. Batteries and electric motors are sized on the distance and speed the vehicle can be driven on electricity alone before the internal combustion engine is required to provide additional power for higher speeds and to recharge the battery[3]. The drive train configuration is thus a trade-off between the higher costs and weight of larger electric motors and batteries and the distance and speed the vehicle can operate using battery electricity only. Typically, this distance is somewhere near average commuting distances, for example the GM Volt is designed to operate for 40 miles on electricity only[4], although the prototype Toyota Prius is being designed for about ten miles electric-only operation because of concerns about the costs of the additional battery capacity. Both the Volt and Prius PHEVs have lithium-ion batteries. Range anxiety is not an issue with PHEVs as the vehicle can continue to operate on petrol once the electricity charge has been used up.

1.2 Approach

To investigate the impact of electric vehicles on the electricity supply system, it is necessary to overlay the electric vehicle demand for electricity over the increasing demand for electricity in other sectors. This requires an estimation of the level of uptake of electric vehicles over time and the associated electricity requirement to power these vehicles.

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[2] The battery capacity of the newer Toyota Prius HEV models is 1.3 kWh.
[3] The electric motor delivers high torque at low speed, making it ideal for accelerating from a stationary position.
[4] With a 40 mile electric-only range, the Volt is designated a PHEV-40 vehicle.

A generation expansion model is used to determine the new electricity generation capacity required to meet electricity demand and to compare it with the likely capacity expansion with no electric vehicle uptake. An important factor in determining generation capacity requirements is the impact of charging electric vehicles on peak electricity demand and whether vehicle charging coincides with peak demand for other electricity uses. This necessitated a review of New Zealand driving patterns and where and when vehicles are likely to be located for battery charging.

There is considerable uncertainty and debate as to the rate of future uptake of electric vehicles. Commercialisation will depend on a number of inter-related factors including the future development and economics of electric vehicle technologies. Consequently, four uptake scenarios have been developed based on other electric vehicle studies, none of which investigated the electricity supply-side impacts in any detail. The steps taken in carrying out this study are summarized as follows:

- Electric vehicle technology was reviewed to ascertain the availability and performance of electric vehicles and their potential commercialization and rates of electricity consumption.

- Vehicle driving patterns were reviewed to determine likely electric vehicle usage and identify possible options for the location and timing of battery charging. This review was based primarily on data developed by Ministry of Transport surveys.

- Electric vehicle uptake and charging scenarios were developed to determine future demand for electricity and options for battery charging at different power ratings and times of day. Electricity demand was determined using a simplified fleet model.

- The impact of battery charging on electricity distribution company overhead and underground feeder lines was analysed, evaluating harmonic voltage effects and the voltage drop along feeder lines.

- The four electric vehicle scenarios were evaluated in the generation expansion model and compared to a base case with no electric vehicles over a 30 year time frame. Primary outputs were the changes in the capacity and type of new generating plant, consumption of fossil fuels, relative costs of generation and any impact on the electricity transmission network.

- Battery charging technology was reviewed and the potential to utilize vehicle charging as a controllable load in the electricity supply system discussed.

- The potential changes in carbon dioxide emissions from fossil fuels used in electricity generation and conventional vehicles displaced by electric vehicles were estimated.

1.3 Acknowledgements

1.4 Acronyms

A   Ampere

Adc   Ampere direct current

BEV   Battery (only) Electric Vehicle

CNG   Compressed Natural gas

CO_2 Carbon Dioxide

dc   Direct Current

EIA   Energy Information Agency (of US Department of Energy)

EPEC   Electric Power Engineering Centre

EV   Electric Vehicle

GEM   Generation Expansion Model

GWh   Giga Watt-hour

HEV   Hybrid Electric Vehicle

ICE   Internal Combustion Engine

kg   Kilogram

km   Kilometre

kWh   Kilo Watt-hour

LFP   Lithium Iron Phosphate

LV   Low Voltage

MCB   Miniature Circuit Breaker

MED   Ministry of Economic Development

MW   Mega Watt

MoT   Ministry of Transport

PQ   Power Quality

PCC   Point of Common Coupling

PHEV   Plug-in Electric Vehicle

SUV   Sport Utility Vehicle

THD   Total Harmonic Distortion

V   Volt

VA   Volt-Ampere

VKT   Vehicle Kilometres Travelled

Wh   Watt-hour

2 Outlook for EV Commercialisation

Despite the progress being made in the development of EV technology, there remain significant constraints to its commercialization in the short term, particularly in respect to BEV technology. Opinion is divided as to if and when and under what circumstances these constraints may be resolved so there is no consensus as to the probable timing and size of the uptake of electric vehicles. The key constraints as identified at this stage in the development of electric vehicles:

2.1 Battery technology: cost and performance

The high cost and low energy density of EV batteries remain fundamental constraints to EV commercialisation although there is considerable optimism that these will be largely resolved in the longer term, for a significant sector of the automobile market at least. Already there has been significant progress in increasing battery energy density as illustrated in the following diagram:
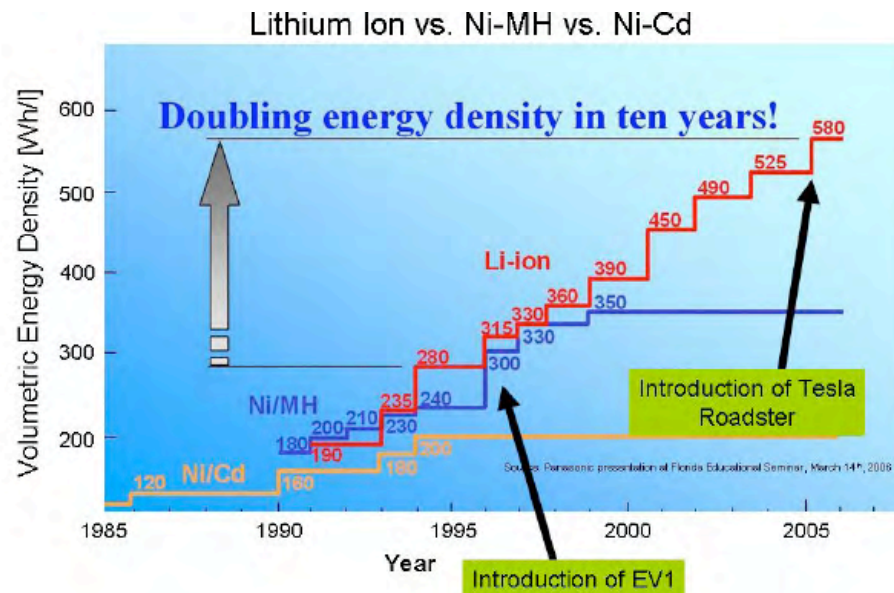
Figure 1: Battery Energy Density Trend[5]

Lithium-ion batteries currently have an energy density by mass of about 100Wh/kg and, with BEV batteries weighing in the order of 150 to 250 kg, typical battery capacities are in the range of 15 to 25 kWh[6]. At the higher end, the BEV Tesla Roadster has a battery weight of 450 kg and, with a stated energy density of 118 Wh/kg, a battery capacity of 53 kWh.

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[5] Response to the CARB ZEV Expert Panel Position on Lithium-Ion Full-Performance Battery Electric Vehicles, Andrew Simpson, Tesla Motors Inc., March 2008
[6] Economic Viability of Electric Vehicles, AECOM Australia Pty Ltd, September 2009

The performance of the various battery technology options is summarized:

- Nickel-metal hydride: a stable and mature technology with typically long life times. They have a relatively low charging efficiency (70%) but with energy densities of up to 80 Wh/kg. These batteries are used in current HEVs but are likely to be superseded by lithium-ion technology.

- Lithium cobalt dioxide ($LiCoO_2$) and lithium manganese oxide ($LiMn_2O_4$): are earlier versions of lithium ion technology, the former used widely in portable consumer electronics. It has a relatively high power density but poses significant safety (oxidation, fire) and durability (reduced capacity with time) concerns for the larger batteries used in electric vehicles. The battery is normally a series combination of individual cells (or a series combination of paralleled cells) making up the EV bus voltage (typically around 300Vdc nominal). Failure of one cell can cause its neighbours to combust, igniting the whole pack almost instantly. Only Tesla appears to be using this technology in electric vehicles, incorporating safeguards to ensure a failure in one cell does not ignite its neighbours. Lithium manganese oxide has higher power and lower cost than cobalt but a lower energy density.

- Lithium iron phosphate ($LiFePO_4$/LFP): is a more recent lithium-ion variant, finding favour due to its stability and safety and the relatively low cost of the compound. It is suitable for large batteries for electric vehicles where safety is a key consideration as it can fail without overheating. LFP batteries have an energy density by mass of just under 100Wh/kg. They have a longer lifetime and peak power rating compared with traditional lithium-ion batteries but up to 60% lower power density.

- Lithium Titanate: a lithium-ion battery with lithium titanate on the anode surface instead of carbon, providing greater surface area and hence faster charging than traditional lithium-ion. A strong candidate for EV storage.

- Lithium sulphur (LiS): is attracting considerable attention for use in electric vehicles because of its potentially high energy density due to the low atomic weight of lithium and the low cost of sulphur. Its chemistry differs significantly from lithium-ion batteries having a lithium anode and sulphur cathode, the latter generally mixed with carbon to enhance conductivity. LiS batteries may be able to achieve 350Wh/kg energy density but some safety concerns have yet to be solved, possibly with quality charging control.

- Sodium sulphur (NaS): analogous to LiS but operating temperatures over 300 °C making them unsuitable for electric vehicle electricity storage. They have high energy density, long cycle life and high charge and discharge efficiency (90%)[7].

With lithium iron phosphate and lithium titanate batteries beginning to offer safe and usable battery options,, it is likely that the next generation of batteries will combine high safety, reliability and energy density, giving electric vehicles lower battery costs or greater capacity and hence range, or most probably a combination of both, and will require more electrical energy to fully charge. In the longer term, and provided safety issues can be resolved, the high energy density of LiS battery technology suggests it is not unreasonable to postulate that electric vehicle stored energy capacity may double, triple or even quadruple over the next 5, 10 or 20 years.

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[7] Whilst charging efficiencies of the different battery technologies differ, a consistent set of comparative data for future performance of all technologies is not readily available. A 90% charging efficiency is probably conservative for determining future electricity demand in this study.

2.2 Electric Vehicle Availability

Following the success of HEVs and improvements in battery technology, a number of manufacturers have started or have plans for imminent production of electric vehicles, in both the BEV and PHEV format. There are common inter-related features to all models:

- They are expensive compared to their petrol or diesel vehicle counterparts due to the cost of batteries, the relatively small scale of production and, in the case of PHEVs, the complexity of the vehicle drive train.

- Scale of production is small because of the high cost of the vehicles and uncertain purchasing response of the wider motoring public.

- Vehicle range for BEVs between recharging is small relative to petrol and diesel vehicles because of the low energy density of current battery technology. Electric-only range of PHEVs is limited by the size, weight and cost of the additional battery capacity.

The following table summarises surveys of electric vehicle manufacturing undertaken during two recent studies[8]. In the context of the total automobile market, these developments are small but represent significant confidence in electric vehicle technology.

Make	Model	Launch	Type	Range	Battery	Capacity	Production Volume pa
Mitsubishi	iMiEV	2009	BEV	125	Li-Ion	16	2,000 up to 30,000 in 2013
Nissan	EV	2010	BEV	160	Li-Ion	24	50,000
Mini	E	2010	BEV	240	Li-Ion	35	500 (pilot)
Ford	Focus EV	2011	BEV	130	Li-Ion	23	8,000
Renault	Fluence EV	2011	BEV			24	40,000 up to 80,000 in 2012
smart	Ed	2007	BEV	115	Zebra	13	1,000 (pilot)
TH!NK	City	2007	BEV	180	LFP	26	7,000 up to 70,000 in 2012
Blade	Electron	2008	BEV	120	LFP	16	200 up to 5,000 in 2011
Tesla	Roadster	2008	BEV	395	Li-ion	53	1,500-2,000
Energetique	evMe	2009	BEV	200	LMP	40	build-to-order
Subaru	Stella	2009	BEV	90	Li-Ion	9	170 (pilot)
Tesla	Model S	2011	BEV	260	Li-Ion	42	20,000 in 2013
Chevy	Volt	2010	PHEV	65	LFP	16	10,000 up to 100,000 in 2011
Ford	Escape PHEV	2012	PHEV	50	Li-Ion	10	5,000
oyota	Prius PHEV	2010	PHEV	20	Li-Ion		500 (pilot)
Chyrsler Sedan18		2012	PHEV			22	
BYD	F3DM	2008	PHEV	100	LFP	13	6,000 up to 24,000 in 2010
Fisker	Karma	2010	PHEV	80	Li-Ion	23	up to 15,000 in 2012

Table 1: Electric Vehicle Models

The same studies estimate the future costs of electric and conventional vehicles. Electric vehicles presently are at least 50% to 100% above those of their petrol engine counterparts, primarily due to the small scale of production of electric vehicles and the high costs of battery manufacture. Batteries presently cost about US$1,000 per kilowatt-hour or typically over half of the cost of manufacturing a BEV. In the case of PHEVs, this proportion will depend on the designated electric-only operation but will be less than that of a BEV because of the latter's simpler drive train and the smaller battery size generally fitted to PHEVs. There is general agreement that this battery cost can be substantially reduced through higher volumes and better production methods, more conservatively estimated by two thirds in 2020[9]. Other sources predict that costs will eventually fall below US$200 per kilowatt-hour and, combined with the benefits of mass-producing complete vehicles, will bring the cost of electric vehicles in line with conventional vehicles in 2030[10].

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[8] *op cit* AECOM and "National cost-benefit assessment of the early uptake of electric vehicles in New Zealand — Methodology, assumptions and results", Hyder Consulting (NZ) Limited
[9] John German, International Council for Clean Transportation
[10] *op cit* Aecom*, op cit* Hyder

The convergence of the cost of electric and conventional vehicles is an important indicator of the uptake of electric vehicles as the majority of buyers look for a quick payback on additional vehicle capital costs when evaluating alternative fuel options:

- During CNG programmes both in New Zealand and offshore, private motorists and owners of commercial passenger cars such as taxis often looked for paybacks on capital costs of conversion of less than one year.

- In the United States, paybacks on the most popular hybrid, the Toyota Prius, have ranged between about 3.5 and 6 years[11] over the last two years and sales of hybrids are generally less than 3% of total vehicle sales, indicating that the level of savings from the improved fuel economy is only attractive to a relatively small number of motorists travelling significantly greater than average distances or to technology "early adopters".

- In New Zealand, Toyota sold 386 Prius in 2008 compared to over 15,000 'New Zealand new' car models[12], with a payback of some six years compared to a Camry, suggesting that the differential in purchase cost should be substantially reduced below the current level of $6,000 to achieve a substantial market share.

- Whilst the fuel cost saving between an electric vehicle and a conventional vehicle is anticipated to be greater than that for an HEV like the Prius (55%[13] compared to 45%), the difference is not so great to sustain a significant purchase price premium. It is anticipated therefore that electric vehicles will only achieve a significant market share when their purchase price approaches that of conventional vehicles. Fuel cost savings for electric vehicles in 2040, at the end of this study period, will remain about the same if there is some increase in ICE efficiency as is generally predicted[14]. However, the saving will fall to below 30% if the typical "conventional" vehicle at that time should be a hybrid petrol vehicle

The availability and competitiveness of electric vehicles will be a balance between the demand for vehicles and manufacturing capacity. Vehicle price will influence demand and will be influenced by the scale of manufacturing and advances in battery technology. Major expansion of capacity will be required before electric vehicles become competitive and may be accelerated by subsidies for resource, climate change[15] or other environmental benefits but expansion is likely to be erratic as supply catches up with demand especially in the next few years if demand remains small. If and when electric vehicles become a significant part of the national vehicle fleet remains conjecture but it is not unreasonable, given the advancing state of technology, that this could be the case in twenty years time.

[11] Based on an average annual distance of 15,000 miles and fuel consumption data listed in the US DoE/EPA's Fuel Economy Guide, 2009. The payback will vary with the prevailing prices of petrol and the listed prices of the hybrid and conventional vehicle, in this case a Camry 2.4 litre saloon.
[12] NZ Transport Agency. The New Zealand payback on the Prius is about six years compared to the Camry based on current Toyota list prices (www.toyota.co.nz), current petrol prices and average distance travelled of 12,235 km pa.
[13] Fuel cost including RUC. Whilst EVs are currently exempt RUC to promote their use, it is probable that this exemption will be revoked once they become cost competitive with ICE vehicles. If RUC is excluded, the fuel cost saving is about 75% at current prices.
[14] Assuming an oil price of US$120/barrel and wholesale electricity prices increasing 1.6% pa through to 2040. See Section 7 for assumptions on energy prices used in the study.
[15] Climate change benefits (reductions in CO_2) will not be the same in all countries as they depend on the type of electricity generation used to charge the vehicles. China for example, with a preponderance of coal-fired generation, will achieve relatively low benefits. Even in this case, it is possible that the addition of the potentially controllable battery-charging load will facilitate greater penetration of non-dispatchable renewable energy generation, such as wind power.

As a very small market, New Zealand is likely to have a very limited impact on driving these developments. Policies such as subsidies may advance the uptake of electric vehicles here but, without an indigenous automobile industry, mass availability of electric vehicles and major technical advances will be dependent on developments in large overseas markets and policies adopted in other jurisdictions.

2.3 Support Infrastructure

The road transport sector involves a wide network of supply and service industries, including fuel and lubricant supplies; new and second-hand vehicle sales; parts, battery and tyre supplies; vehicle testing; servicing and repair of vehicle mechanics and bodywork; and the training of technicians. All these activities are well established throughout New Zealand.

Electric vehicles will require all of these services with the obvious exception of petrol and diesel supplies in the case of BEVs. The only new technology presented by electric vehicles will be the electrical system, notably motor, generator and braking systems, and the supply, servicing and disposal/recycling of batteries. There is considerable experience within both the automobile and general industry with items such as electric motors and generators so the transfer of expertise to this area is very unlikely to present difficulties. Dealing with large numbers of large batteries does present some novel activities, particularly with respect to disposal or recycling of used batteries, which will require some planning and possibly the establishment of a new service industry.

At this point in time, it is very unlikely that the support infrastructure will cause an impediment to the introduction of electric vehicles provided that adequate forethought is given to such issues as battery disposal and the appropriate training of technicians. The anticipated slow uptake of electric vehicles in the near term provides opportunity to address these issues. This will best be managed with an industry-wide approach coordinating government, vehicle suppliers, service industries and training institutions. This was successfully achieved in the 1980s when the government led the CNG programme which, after some initial quality problems, developed a successful industry imitated by a number of other countries. Without the coordinated approach and establishment of the necessary service infrastructure the programme would not have succeeded as poor quality of services will quickly lead to consumer resistance to new technologies as happened in the early stages of the CNG market.

Provision of electricity and the associated vehicle charging options are essential components of these services for electric vehicles and are discussed in detail in later sections of the report.

2.4 PHEVs versus BEVs

Both PHEV and BEV models have been released or are about to be released by various manufacturers over the next year or two. BEV manufacturers have concentrated on the smaller (Mitsubishi iMiEV) and medium (Ford Focus EV and Nissan Leaf) size vehicle categories. Claimed maximum operating range between battery charges typically falls in the range of 110 to 180 km, being limited to by the size and costs of the battery used[16].

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[16] These batteries typically have capacities of 15 to 25 kWh and an overall vehicle energy efficiency of some 7 km/kWh. A more conservative figure of 5.7 km/kWh is used throughout the analysis in this study to account for more rigorous driving patterns and parasitic demands on the battery such as vehicle air conditioning. It is not expected that this will improve significantly as the electric motor already operates to a high level of efficiency.

This range is expected to increase significantly as the battery energy density is improved as expected allowing more energy to be stored in the same weight of battery. The high cost and limited range[17] of the current BEV models are seen as the main impediments to the uptake of BEVs in present mass vehicle market.

PHEVs provide a partial solution to these concerns with BEVs by complementing the battery range with petrol operation to extend total vehicle range to levels comparable with ICE vehicles. There is a compromise between maximizing the electric-only range of the PHEV and reducing the battery weight and cost. Vehicle manufacturers have taken different approaches when setting the electric-only range: the BYD F3DM has range of 100 km, the GM Volt 65 km, whereas the Toyota Prius plug-in has an electric-only range of only 10 km. Toyota's conservative approach stems from concerns about consumer resistance to the high cost of extra battery capacity, the unproven technology, and uncertainty about how customers will operate the vehicles.

Because of the extended range of PHEVs it is commonly believed that they will be more readily accepted by the market in the shorter to medium term. However, as battery densities increase and costs fall, the range disadvantage of BEV relative to both PHEV and ICE vehicles will diminish and BEV will become the predominant electric vehicle technology as it is a simpler technology than PHEV and potentially cheaper when battery costs are reduced substantially.

It is open to conjecture when that cross-over will occur and what the electric-only range of PHEVs will be in ten or twenty years' time. For these reasons, it is assumed when determining electricity demand in this study that both types of electric vehicles will operate on electricity only. This is a conservative assumption as it discounts petrol used on longer trips by PHEVs but not unreasonable given that the electric-only range of some PHEVs is already well in excess of the average daily distance travelled by vehicles (Section 3) and PHEVs will preferentially operate on electricity than petrol[18]. No distinction is made between the electric-only performance of PHEVs and BEVs.

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[17] Compared to over 500 km for ICE vehicles, which can be refueled quickly at service stations.
[18] It is estimated that electricity would have to be priced at over 90 c/kWh to match the energy cost of petrol with oil priced at US$120/barrel (RUC included).

3 Driving Patterns and Vehicle Charging Options

Charging of electric vehicle batteries will differ considerably from the fuelling of ICE vehicles as the rates of charging batteries are considerably slower than pumping fuel and electricity is available at households allowing EVs to be plugged-in for charging over extended periods. This section reviews vehicle usage patterns to identify possible battery charging options which are important determinants of peak electricity demand from electric vehicles.

3.1 Daily Driving Distances

Light petrol and diesel passenger vehicles account for 78% of New Zealand road transport vehicle kilometres (VKT)[19]. This category of vehicles, along with light commercial vehicles which contribute a further 14% of total VKT, represent the primary target market for electric vehicles as they are predominantly four wheel vehicles of less than 3.5 tonnes weight.
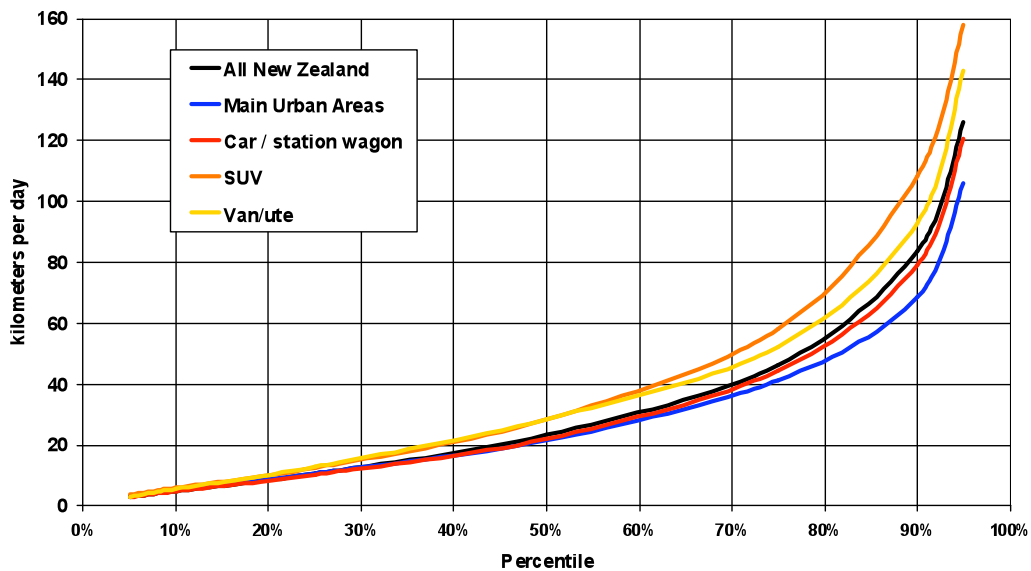

Figure 2: Private Vehicle Use

Private vehicles are used on average slightly less than one hour per day, travelling some 39 kilometres[20] and averaging about three trips each day including the return trip home. Cars travel slightly less (37 km) as SUVs and van/utility vehicles average somewhat over 45 km. Distances travelled in rural areas and smaller towns average over 52 km per day whereas those in the major urban centres average 34.9 km.

As the median distance travelled per day of 23.2 km is significantly less than the average distance, a disproportionate amount of total VKT can be apportioned to a relatively small number of vehicles. The distribution of travel amongst private vehicles is shown in Figure 2.

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[19] Transport Monitoring Indicator Framework, MoT, 2009. VKT is the aggregate distance travelled by a group of vehicles.
[20] Ongoing Household Travel Survey, 2003-2007 data, Ministry of Transport. MoT's Transport Monitoring Indicator Framework graphics and fleet data indicate a lower average for light vehicles (combined passenger and commercial) of about 33.5 km/day. This lower number is used in the fleet VKT modeling,

It shows that 95% of vehicles travel less than 126 km/day and, with a daily average of 39 km, it can be deduced that 5% of vehicles account for about 25% of total VKT travelled by private vehicles (this same proportion applies in the main urban areas despite the 95 percentile being only 106 km per day). Only 0.4% of trip chains are longer than 150 km in driver distance[21].

VKT is directly related to energy consumption, in the case of electric vehicles the electrical energy required to charge the batteries. Average annual VKT per vehicle for light passenger vehicles in New Zealand was 12,235 km in 2007 and remained relatively constant over the immediate preceding years. For the purposes of this study, it is assumed that the average travel distance of electric vehicles through to 2040 is 12,235 km per annum and the inclusion of light commercial EVs will add a further 18.4% to the aggregate VKT of light passenger EVs[22]. This is a simplifying assumption in the determination of electricity demand for electric vehicles but its impact is small compared to any assumptions around the uptake of electric vehicles in the New Zealand market. Whilst the population of electric vehicles has been modelled (Section 4), aggregate VKT has not as it is related to future demand for transport and beyond the scope of this study.

3.2 Trip Purpose and Vehicle Parking

Trip purpose and vehicle parking patterns provide indications as to where electric vehicles can be charged. Vehicle use patterns may change in the future as drivers adapt to the particular characteristics of electric vehicles compared to ICE vehicles but as there is no authoritative data in New Zealand which describes any potential change in behaviour, data is drawn from surveys carried out by the Ministry of Transport of current vehicle use[23].

The survey data indicates that more than 90% of vehicles are parked overnight at home from 10 pm to 6 am during weekdays (Figure 3 below). From 6 am vehicles are parked at work, home or at other locations until the early evening and by 6 pm 80% of vehicles are parked at home. During the weekend the parking pattern is somewhat different with significantly more vehicles parked at home during the daytime and only a small number taken to work. A slightly smaller proportion of parked vehicles are located overnight at home during weekends.

Figure 3 also shows the daily distribution of hours all vehicles in New Zealand were parked during a surveyed year period. It indicates (by the dip in the narrow black lines) that most driving takes place during daytime hours and that the very large majority of vehicles are parked at night, predominantly at home. This is most pronounced during weekdays when a lesser number of cars are parked during the daytime hours, especially during the work and school rush hours of 6 to 9 am and 3 to 6 pm. The small magnitude of the dip in the graph confirms light vehicles are utilized on average for only a short time each day, travelling less than 40 kilometres.

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[21] A trip chain is a series of trips which ends at home, at work or when followed by a stop of 90min or more.
[22] In proportion to their contribution to total New Zealand VKT. Light commercial vehicles averaged 14,375 km per year in 2007.
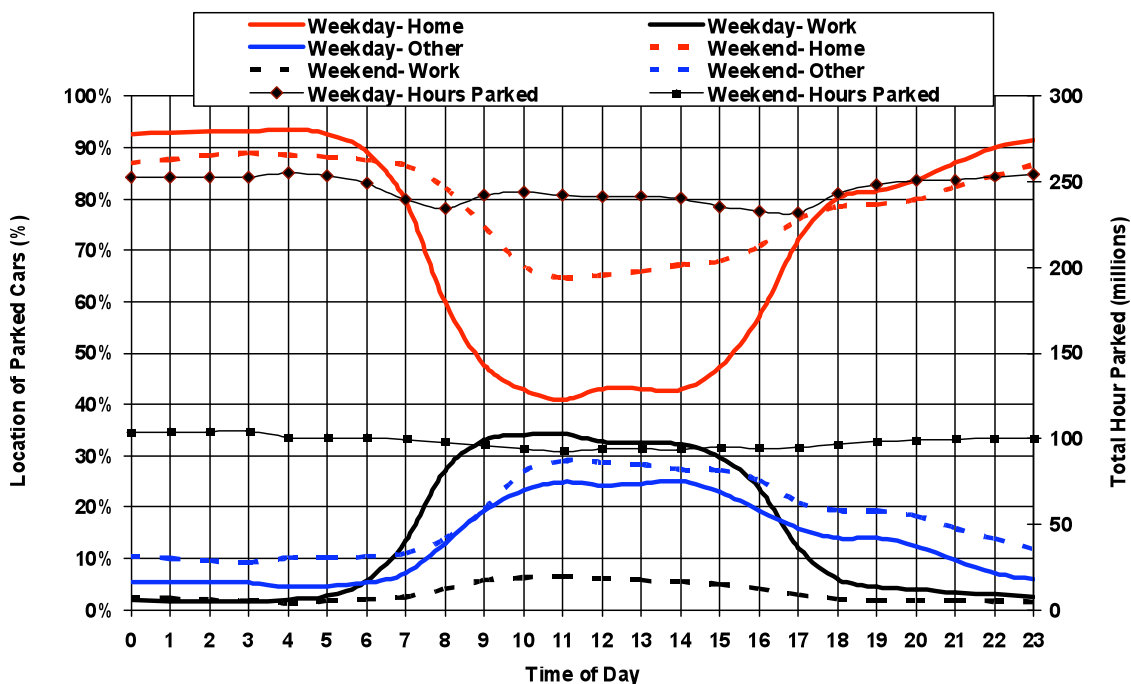[23] Ongoing Household Travel Survey, 2003-2007, Ministry of Transport

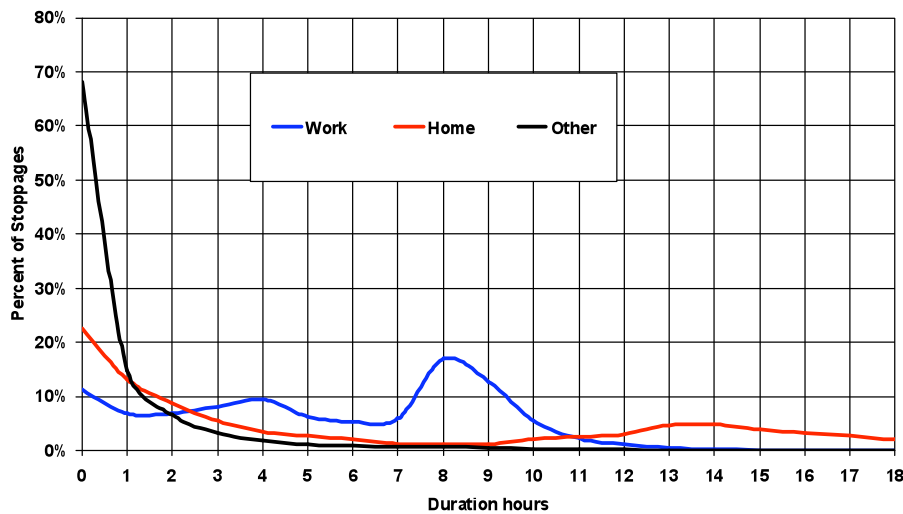**Figure 3: Light Vehicles: Parking by Time of Day**

Figure 4: Duration of Vehicle Stops

The duration of stops when parking also provides an indication of the best time to be charging electric vehicles. Average duration of stops of vehicles at home is over seven hours, about one third for durations of less than two hours, due to day-time activities, and a further third of home stops between 8 and 20 hours duration. However, the survey methodology probably under-represents the final return home in the evening, suggesting that home stops are mainly of longer duration[24].

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[24] The survey of stop duration excludes the final stop in the survey period, which will have an unknown length. This will tend to under-represent the stop after the return trip home which will most often be the overnight parking of the vehicle.

Average time for parking at work is nearly six hours with a peak at eight and nine hours whereas over two thirds of vehicle stops other than at home or work are for periods of less than one hour.

The parking duration and location patterns are reflected in the survey of the purpose of individual trips undertaken by vehicles. About one third of all passenger vehicle journeys terminate at home with the remaining two thirds split between a variety of activities (Figure 5). Of the latter, some 10% of trips in terms of both trip numbers and distance are taken in driving to work, suggesting that about 20% of total VKT (including weekends) is spent driving to and from work. This more or less corroborates with about one third of vehicles parked at work during the middle hours (8am to 4pm) of weekdays as depicted in Figure 3.
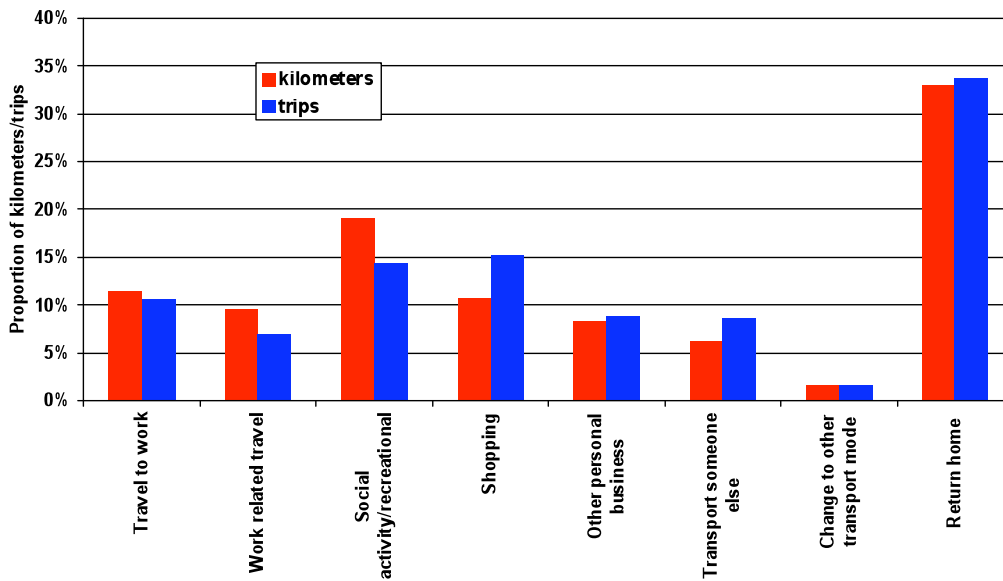

Figure 5: Purpose of Travel

A more detailed examination of the location of parked vehicles provides further insight as to where the best conditions for recharging vehicles exist. Figure 6 shows that 90% of vehicles are parked overnight[25] on the residents' property and 4% on off-street private parking as opposed to parking on the street or other public areas. This proportion is somewhat lower in urban areas where street parking is more commonplace but no lower than 86% parked on the street in the Wellington region. About three quarters of vehicles stopped for work for durations over 4 hours are parked in private off-street locations, suggesting there is an opportunity to recharge a significant number of vehicles whilst in a safe environment at work.

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[25] Overnight parking defined as parking after the last recorded vehicle trip of the day
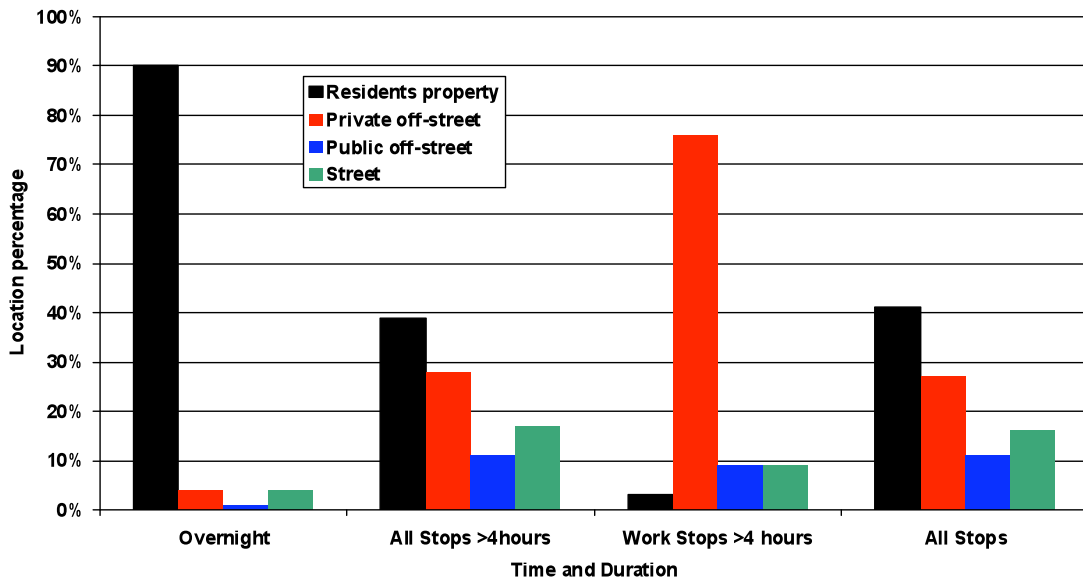
Figure 6: Location of Vehicle Stops

This analysis of vehicle driving patterns suggests a number of opportunities for charging electric vehicles:

- Over 90%[26] of light vehicles are parked overnight at private residences or at private off-street locations, with the very large majority parked at home between 6 pm and 6 am. A long average duration of night time home vehicle stops and the facility to recharge vehicles from household electricity provide an opportunity for extended overnight periods of slow vehicle recharging in a safe environment during a period which overlaps with otherwise low electricity demand.

- A significant number of vehicles is parked at private off-street sites during weekday work hours. It is estimated that up to 25% of vehicles may be parked at work in potentially safe situations for recharging during this period, which extends between 8 am and 4 pm.

- About 40% of vehicles are parked at home at any time during weekday daytime and about two thirds of vehicles at weekends. The durations of the stoppages are likely to shorter than overnight but nevertheless suggests recharging can be undertaken for a significant number of vehicles using household facilities.

- Over two thirds of vehicle stops other than at home or work are for periods of less than one hour. With a greater bias towards parking in the street or other public areas, opportunities for daytime slow charging in public places therefore may be limited. Alternatively, "fast charging" public facilities could be used to meet daytime demand.

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[26] This figure may be about 4% lower for the Wellington region. It is often commented that many cars are parked on the streets overnight in Wellington. This is a characteristic of Wellington's inner suburbs whereas the Wellington region includes Wellington's outer suburbs, the Hutt Valley and Porirua where most residential properties have off-street parking.

3.3 Vehicle Charging Options

Battery charging rates at households will be constrained by the capacity of electricity distribution networks. For example, a current electric vehicle battery[27] is specified for recommended charging[28] at a current of about 45Adc up to a maximum[29] of some 270Adc, requiring a power input of 10kW and 78kW respectively[30], which is beyond the scope of a normal household power supply. Whilst the peak capacity for households is 12 to 13kVA per connection, the low voltage network is designed, assuming diversity, for an average load per connection at peak demand times of about 5kVA[31]. Orion has indicated an ideal domestic vehicle charger capacity should be near the peak demand average load to provide best potential for load control, i.e. 4 to 5kW at a power factor close to unity[32].

Several rates of battery charging are available consistent with household electrical wiring constraints and the maximum recharge rate of the vehicle batteries:

- 2kW charger, powered from a 10A socket. This is consistent with present household loads and will require no upgrading of wiring.

- 3kW charger, powered from a 15A socket or hard-wired. Again consistent with household loads but will require some minor wiring modification.

- 4 or 5kW, the normal maximum household charging level expected. In the short term, Orion expressed a preference for this to be powered from a ripple controlled switched outlet, but in the longer term "smart grid" technology would provide a number of power system benefits. This supply will probably require a dedicated MCB on the house main switchboard and associated wiring. This can easily be implemented by an electrician, in much the same way as an electric cooker or heat-pump is installed.

- 13kW charger, drawing nearly 60A from a single-phase electrical supply, which is at the wiring limit for most households. Effects on the distribution system would be undesirable at this rate unless a three-phase supply is available and is therefore only likely to be available in a small number of cases[33]. Alternatively, a 13kW single-phase charger could be used in a well-controlled public situation with appropriate communications and control infrastructure.

- 78kW represents the current maximum charging rate of vehicle batteries and would reflect the performance of likely public "fast" charging facilities. A number of vehicles could be charged simultaneously, requiring about 1MVA for every 12 vehicles charging simultaneously.

Note there is limited verifiable performance data available for electric car batteries, thus the relative efficiency of charging at other rates than the recommended C/2 or 3C rates is unknown, as well as the potential effects on the lifetime of the battery.

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[27] LiFePO4 cells with a nominal capacity of 26 kWh
[28] C/2 where C represents the total capacity of the battery, that is it can supply C A for 1 hour
[29] 3C
[30] At 230V and a power factor of 0.9 and battery charging efficiency of 90%
[31] Orion: Most Christchurch City LV customer connections are single-phase underground 16mm^2 cables rated for 60A, though some lighter overhead connections still exist. The underground LV network has low impedance and a power factor near unity.
[32] The cell voltage of lithium based battery technologies drops substantially with state of charge and, as constant current charging is recommended, more highly rated chargers are favoured. For example, a LiFePO$_4$ battery on a constant current 5kW charger would only be drawing about 3.8kW for most of the charging cycle, reaching 5kW at the end of charge. Similarly a charger with a maximum rating of 4 kW at constant current will draw only about 3kW for most of the charging cycle.
[33] Based on existing household electricity supplies but could change if and when EVs become popular. However, underground upgrades to 3 phases are costly.

The times to charge batteries at these rates to meet the various percentiles of vehicle daily driving distance are shown in the following table:

Charge Rate kW	2	4	13	78
Daily Distance Travelled				
Average	3.8	1.9	0.6	0.10
75 Percentile	4.5	2.3	0.7	0.12
90 Percentile	8.2	4.1	1.3	0.21
95 Percentile	12.3	6.1	1.9	0.31

Overall vehicle efficiency 5.7 km/kWh/ Charging Efficiency 90%

Table 2: Charging Time to Meet Daily Vehicle Distances Travelled (hours)

Table 2 shows that 95% of vehicles can receive the next day's electricity requirement during a 6 hour overnight charge at a charging rate of 4 kW. At the maximum charging rate it will take about 20 minutes to recharge a battery with a useful electrical capacity of 20 kWh but only 6 minutes to charge the battery sufficiently to travel the average distance travelled daily by private vehicles[34]. Battery swap stations are an alternative to fast charging facilities but will require modular battery packs exchangeable between electric vehicle makes and models, as otherwise a large number of packs would be required, all needing to be charged and topped up waiting for the right vehicle to turn up. Demonstration stations exchange batteries in less than two minutes but the weight of the batteries (about 300 kg) necessitates expensive automated battery handing equipment[35].

3.4 Night Battery Charging

Overnight battery charging presents a number of advantages compared to charging during the daytime:

- Little driving takes place during night hours and most vehicles are parked on residents' property from 6 pm to 6 am, providing a secure environment for vehicle charging.

- Electricity demand is relatively low from 9pm to 7am, allowing the utilisation of unused generating capacity during this period. Load patterns are illustrated in Figure 7 for the Penrose and Islington grid offtake points, which indicates there are potentially about 10 hours available for overnight off peak charging. In some circumstances electric vehicle charging would have to share with other controllable loads such as hot water heating, should more of these loads be diverted to this period[36]. The implications on the electricity supply system of utilising this off peak period for charging electric vehicles are discussed in Section 6.

- The cost of home charging equipment is likely to be small compared to developing public fast charge facilities.

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[34] A charging time of 20 minutes is very long by current refueling standards and would require a significant attitude change by motorists. Experience with the CNG programme indicated drivers switched to petrol rather than spend much time seeking out a CNG station. Public CNG stations had to be designed to fuel vehicles at much the same rate as petrol pumps.

[35] Better Places website.

[36] Orion advises its load in the time between 9pm and midnight is close to capacity at present due to water heating and a more suitable period for electric vehicle charging may be 1am to 7am. However, it is possible that some water heating could be diverted to a later time and the earlier period shared with electric vehicles.
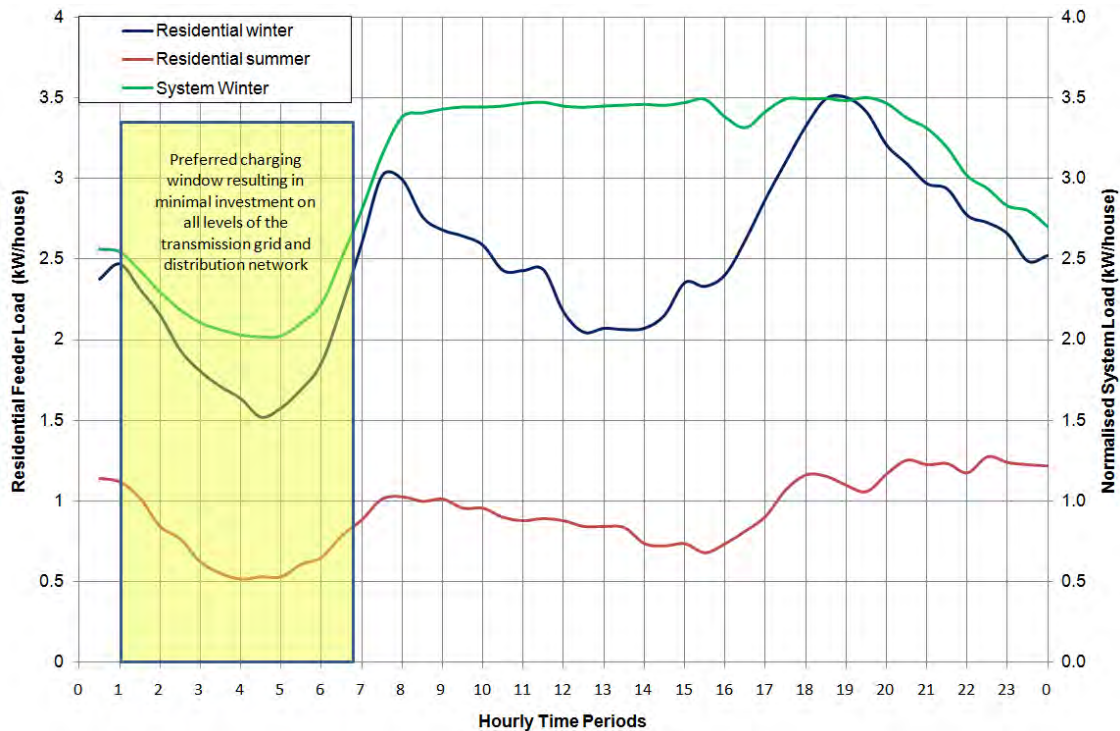
Figure 7: Representative Daily Electricity Demand Pattern (indicative daily household load profile supplied by Orion)

There are however limits to the amount of electricity which can be delivered during this period:

- The rate of single phase battery charging is slow at households. If insufficient time is available during the night period, the battery may not be charged to the requisite level and supplementary charging must be carried out during the following day.

- The battery size may not be of sufficient capacity to store the following day's electricity requirement, necessitating complementary charging during the day.

- The daily vehicle travel data indicates a small number of highly utilised vehicles contributes a disproportionate amount of fleet VKT. These are the vehicles which will be constrained by charging rate or battery size and for whom the shortfall between total charging requirement and that delivered overnight is potentially significant.

Figure 8 shows the proportion of total daily VKT which can be satisfied by overnight charging at different rates of charging and different battery sizes. Vehicles travelling longer distances the following day may not receive sufficient electricity for their journey due to the battery capacity or charging rate constraints discussed above. The proportion of electricity requirement satisfied increases with battery charging rate and greater battery capacities. Where the lines in Figure 8 are horizontal, total VKT charged is limited by the charging time available and by the battery capacity where the lines slope upward.
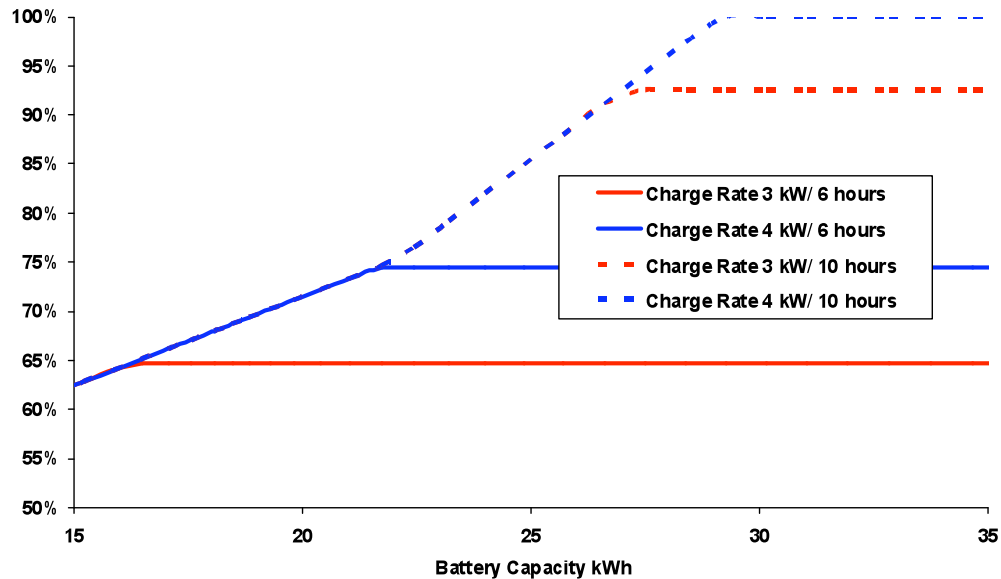
Figure 8: VKT Charged at Night

With a 10-hour window for overnight charging and an effective charging rate of 4 kW, virtually all electricity requirements could be supplied overnight if battery capacity is over about 30 kWh. A relatively small number of vehicles travelling distances in excess of about 160 km would not receive their full requirement but this number would diminish as battery capacity improves. It is likely that a capacity of 30 kWh will be well exceeded within the study period. However, it should be noted that a minority of vehicles will not have access to overnight charging facilities.

Charging patterns will be more complex in practice. Motorists may optimise their charging practices to take advantage of any spare battery capacity and electricity price incentives. In some cases the motorists might anticipate a long distance trip by charging over several nights in advance and conversely a majority of households have access to two or more vehicles[37], which may congest access to domestic charging appliances. The combined effect of these factors is uncertain and justifies further investigation beyond the scope of this study.

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[37] Transport Monitoring Indicator Framework, MoT, 2009

4 Electric Vehicle Uptake Scenarios

The rate of electric vehicle uptake by the New Zealand market will be the primary determinant of EV electricity demand. Technical factors, such as vehicle energy efficiency and battery charging efficiency, have limited scope for improvement over current benchmarks, even during the extended period of this study. As noted in Section 2, there remains considerable uncertainty as to when electric vehicles will be competitive with conventional vehicles and consequently appeal to the mass vehicle market.

4.1 Studies Reviewed

This uncertainty is apparent in the disparity between various rates of electric vehicle uptake determined in several studies reviewed (Figure 9). Hyder and AECOM (a study of the Australian market) use economic modelling to determine the competitiveness of electric vehicles whereas the MoT data is based on a less objective assessment and shows the uptake of both new and used electric vehicles entering the market. The differences in uptake during the early years make substantial differences to the total population of electric vehicles in the national fleet in 2040.
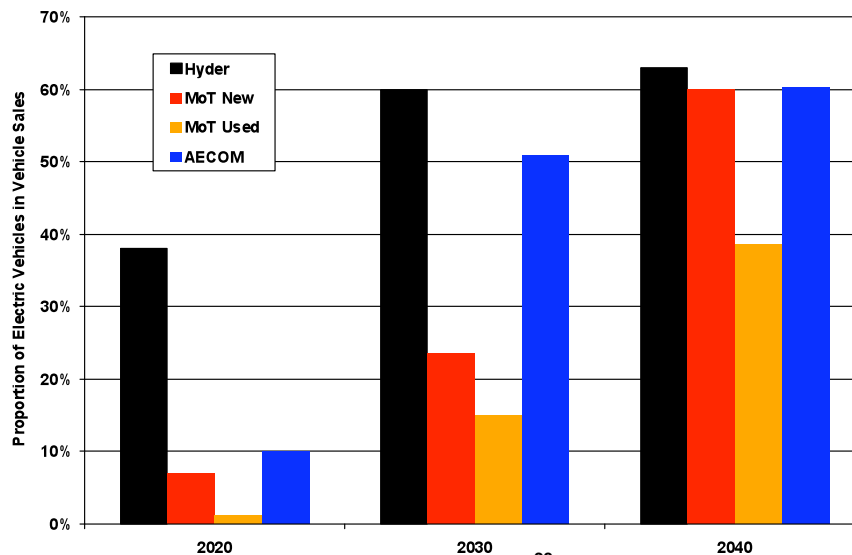

Figure 9: Electric Vehicle Sales in Various Studies[38]

- Electric vehicle uptake in the Hyder study appears at the higher end of estimates, particularly during the early years when electric vehicles comprise 40% of new vehicle sales in 2021, substantially more than the other studies.

- The MoT estimates of uptake are conservative, reflecting concerns with the availability of electric vehicles for the New Zealand market. As shown in Section 6, the demand for electricity arising from this level of electric vehicle uptake is small compared to national electricity demand.

- Other studies arrive at intermediate uptakes. AECOM has three rates of electric vehicles uptake, all between the Hyder and MoT estimates and a recent study by the University of California at Berkeley[39] includes two scenarios resulting in electric vehicle populations within the same bounds.

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[38] Shows the mid-range AECOM scenario
[39] Electric Vehicles in the United States, University of California, Berkeley, 2009. The study period in this paper extends only to 2030.

4.2 Electric Vehicle Uptake Scenarios

This study does not attempt to predict electric vehicle uptake by an economic analysis, as this would entail making conjectural assumptions on the future development of electric vehicle technology. Rather, four scenarios based on the Hyder, MoT and the AECOM work have been chosen to illustrate the uptake of electric vehicles and associated demand for electricity (Figure 10):

1. Lower Case: EV uptake rises to 50% of vehicles entering the fleet in 2040. This approximates the MoT projection.

2. 60% EV Uptake in 2040: deeper market penetration than the base case, similar to the final uptake in the EIA baseline scenario noted in the Berkeley report.

3. 80% EV Uptake in 2040: similar to the final uptake in the Berkeley scenarios, where EVs capture all markets except for some categories of light trucks, SUVs and small buses.

4. Upper Case: rapid uptake of EVs during the early years of EV introduction, similar to uptakes calculated by Hyder.

A base case with no significant uptake of electric vehicles is used in the electricity supply system analysis as a benchmark against which to measure the impact of electric vehicle charging.
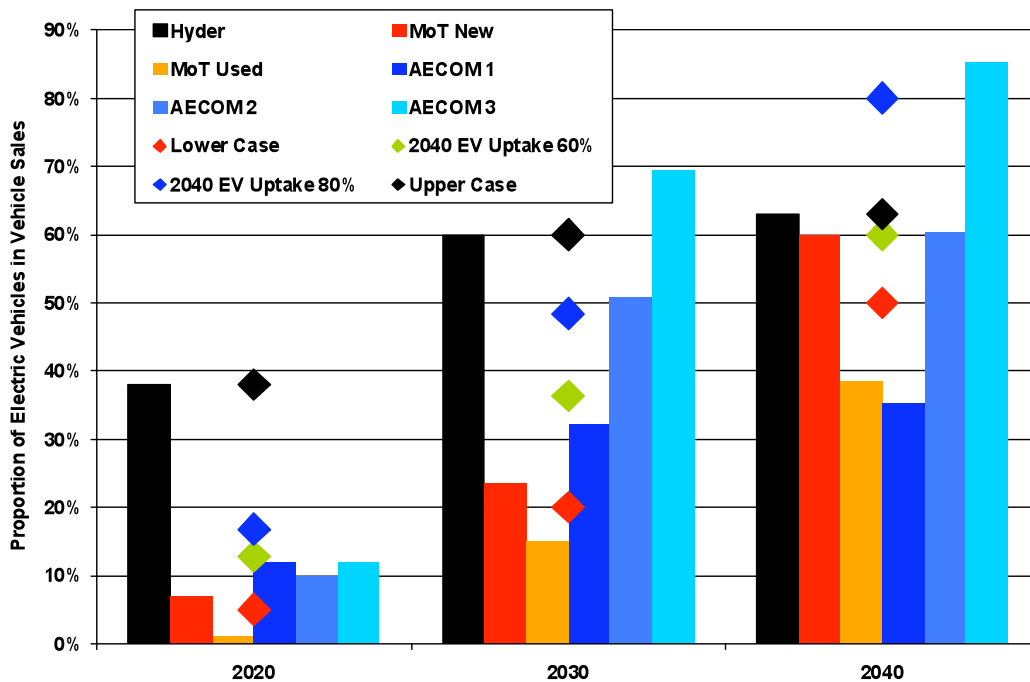

Figure 10: Scenarios: Uptake of Electric Vehicles- Proportion of Vehicles Entering New Zealand Fleet[40]

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[40] No distinction is made between the performance and operation of BEVs and PHEVs. BEVs are likely to predominate over PHEV in the longer term as battery technology and range improve.

4.3 Fleet Model

A fleet model has been used to project the growth of the electric vehicle population in accordance with the following steps:

1. The number of light passenger vehicles in New Zealand grows from a basis of 2.584 million in 2008 to 3.200 million in 2040. This is in line with MoT projections and provides a ratio of about 0.59 vehicles per head of population throughout the study period[41].

2. Vehicles are scrapped each year in proportion to the average rates of mortality for petrol and diesel vehicles in 2008. The mortality profile of electric vehicles is assumed to be the same as petrol vehicles.

3. The number of new vehicles entering the fleet in each year is the difference between the total number of vehicles in the fleet for that year as determined in step 1and the number of vehicles remaining from the previous year after applying the mortality profile. The age profile of the new vehicles is the same as the average for petrol and diesel vehicles in 2008, which includes both newly manufactured and imported used vehicles.

4. Electric vehicles are introduced into the fleet by nominating a percentage of new vehicles entering the fleet as either BEVs or PHEVs. These rates of electric vehicle uptake are as described in scenarios in Section 4.2.

5. The mortality profiles are adjusted to calibrate the model to follow the proportions of petrol, diesel and electric vehicles in the projections provided by the MoT[42]. This is shown in Figure 11 in which HEVs are combined with PHEVs and BEVs.

6. Total electric vehicle VKT in any year is determined from the number of electric vehicles in the fleet and the average annual distance travelled by light passenger vehicles, 12,235 km. No distinction is made between the operation of BEVs and PHEVs. Light commercial electric vehicles add a further 18.4% to the aggregate VKT of light passenger EV vehicles[43].

7. The annual electricity requirement to power the electric vehicle is based on an overall energy efficiency of 5.7 km/kWh adjusted by a battery charging efficiency of 90%. These factors remain constant throughout the study period as there is limited scope for improvement.

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[41] Compared to a mid-range Department of Statistics population projection rising to 5,401,800 in 2041

[42] The MoT vehicle fleet model is based on national vehicle registrations and tracks and forecasts vehicle fleet population, utilisation and composition for both petrol and diesel vehicles of various engine size categories. A separate model determines VKT based on demand for transport and includes the declining use of vehicles with age. The CAE model is a simplified version assuming a constant average VKT per vehicle.

[43] Based on 2008 VKT data for petrol and diesel light vehicles. This assumption implies that the proportional uptake of EVs in the commercial and passenger fleets will be the same. There is no specific evidence as to how these might differ 20 years hence.
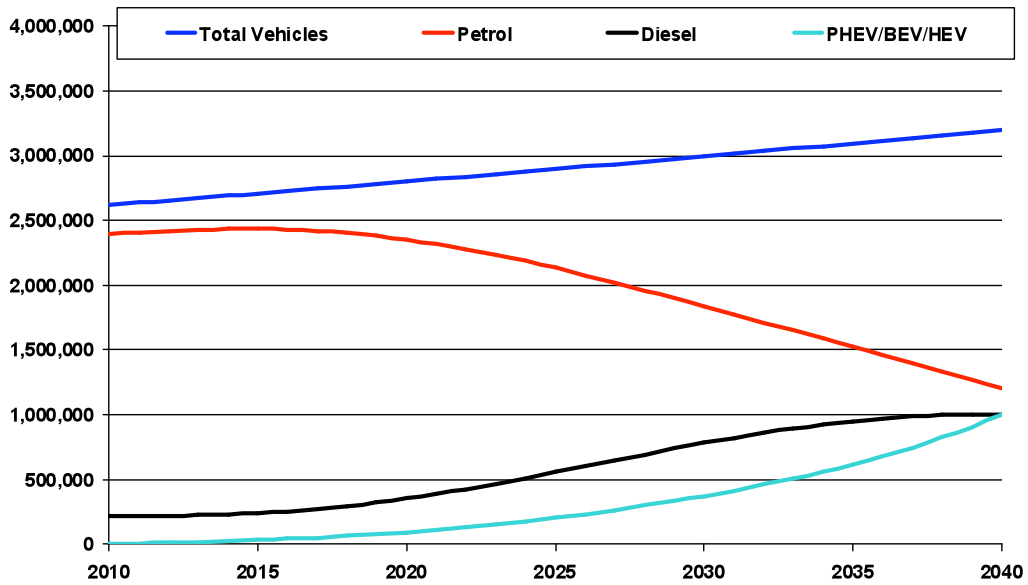
Figure 11: MoT: Light Passenger Vehicles in Fleet

Under the four scenarios, the population of electric vehicles in 2040 will range between about one and two million vehicles and the associated electricity demand between 2,000 and 4,500 GWh per annum (Figure 12):
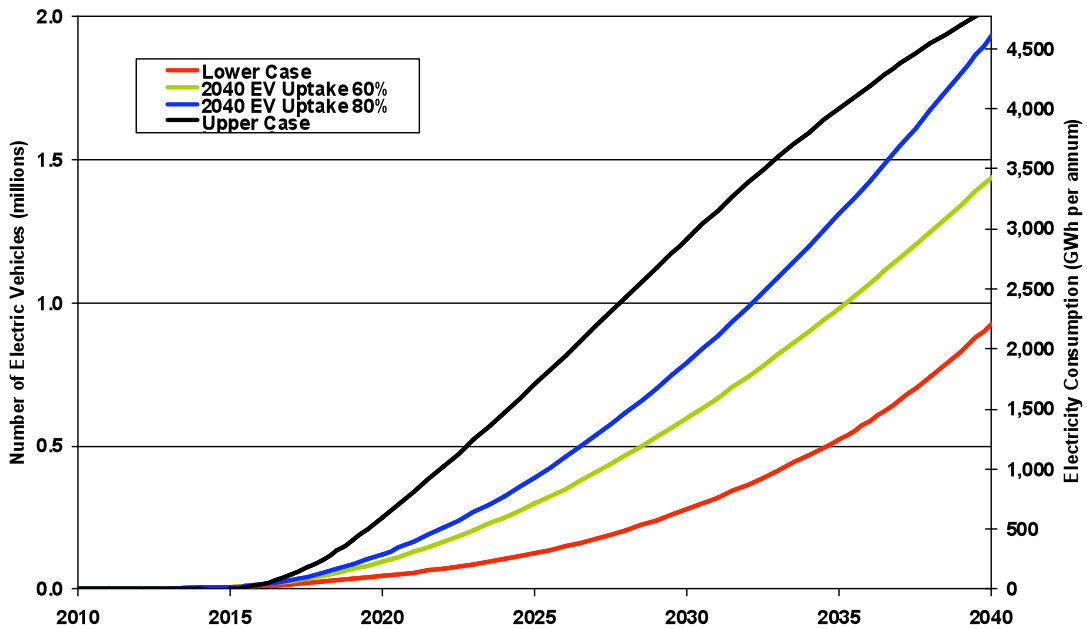

Figure 12: Scenarios: Electric Vehicle Population and Electricity Consumption

4.4 Vehicle Charging Assumptions

Peak electricity demand from electric vehicles will be substantially dictated by the daily patterns of battery charging. The following assumptions have been made for the electricity system analysis:

- Daily demand for electricity for charging will be constant throughout the year. There may be peaks at times such as holidays but there is no firm data on peaks in traffic travel making any assumptions on how this will affect battery charging speculative.

- Home chargers will have an effective 4 kW input and 90% charging efficiency. This is consistent with Orion's preference for chargers of 5 kW capacity and the somewhat lower power actually delivered due to the battery charging characteristics.

- A maximum of 85% of total electricity demand can be delivered overnight to account for vehicles not parked at home and households where battery charging is impractical or unsafe.

- The remaining 15% of charging energy is spread uniformly over the entire day.

- A sensitivity study has been carried out assuming only 50% of vehicle charging is done exclusively during off peak periods and overnight.

5 Impact of Electric Vehicles on Distribution Networks

Local electricity distribution networks will provide the final link between the electricity supply system and electric vehicle chargers. The impact of different numbers of vehicle battery chargers on typical networks has been investigated to determine the level of electric vehicle uptake at which battery charging starts having a significant impact on both localised supply and the network as a whole.

The focus of the work is electricity distribution to urban, residential properties where the majority of battery charging is anticipated to take place. Both overhead and underground feeders are investigated with representative data for length, impedance and load provided by Orion NZ Ltd. Some variation in these characteristics might be expected in distribution feeders around New Zealand, but the data used is suitably representative for the purposes of this study.

The results below form the initial scoping work by the EPECentre, at the University of Canterbury, for a larger more detailed project looking at EV charging infrastructure requirements and impacts. The relevant power quality effects of electric vehicle chargers investigated[44] in the study were:

- Harmonic voltage effects at points of common coupling (PCC)
- Voltage drop along feeders.

Whilst these are significant effects, they do not constitute an exhaustive examination of the impact of electric vehicle chargers on power quality. Only two parameters were selected for this study due to the scope constraints. Further analysis is required for a wide range of other effects caused by high penetration of electric vehicles, including;

- the incorporation of more accurate models for EV chargers based on measured data,
- the interactions of EV chargers with other appliances,
- diversity ranges,
- harmonic allocation levels for EV chargers,
- possible Power Quality standards for EV chargers,
- distribution equipment ratings,
- unbalance effects,
- transients,
- load control,
- and further study of various load situations including multi-car charging.

Further investigation should also be based on the measured characteristics of actual electric vehicle chargers rather than the estimates discussed below as worldwide standards around EV chargers and electric vehicles themselves are still presently in a state of flux.

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[44] Siemens PSS SinCal version 6.0 software was used for the harmonic load flow and voltage drop calculations in this report.

5.1 Distribution Network Characteristics

A typical NZ distribution network takes supply from Transpower's grid at 110kV, 66kV, 50kV or 33kV. For historical reasons, some distribution networks may also take supply at 11kV. Distribution network overhead and underground sub-transmission assets are connected to the higher voltage (33kV to 110kV) grid exit points. These sub-transmission lines and cables supply distribution network zone substations of varying capacity (ranging from less than 1MW up to 40MW).

Zone sub-stations convert the sub-transmission voltages down to 22kV or 11kV for more wide spread distribution to local substations which step the voltage down to 400V.

In urban areas where the high penetration of electric vehicles is expected, the sub-transmission network, zone substation transformers and 11kV network are usually constrained by thermal limitations as opposed to voltage constraints which might occur on the rural network and some of the 400V LV network.

Upgrades to the high voltage network tend to be lumpy in nature and at any given time a large urban network will have areas approaching constraint and areas with spare capacity. The ability to transfer load through open point changes and the relatively short design and build time (2-3 years) for most high voltage network upgrades means that there is little risk that even a fast uptake in electric vehicles would cause a risk to **sub-transmission** network security of supply and reliability. At this level of the network, the focus is on creating an electric vehicle charging regime that either avoids or minimises accelerated sub-transmission network investment. In general, sub-transmission networks are built with redundancy (can withstand a fault of one piece of plant without interruption or quick restoration is possible) and therefore the ability to quickly control EV charging post contingency on the high load days may be all that is required for maintaining sub-transmission security of supply.

However, the distribution substation (11kV to 400V) and low voltage (400V) network is not built with the same level of redundancy and further growth in load on this network can lead to supply constraints. The large scale of the low voltage network (more than 10,000 feeders in the Orion case) has historically prohibited the economic installation of SCADA for real time load indication or even logging equipment to monitor the daily load profile of distribution transformers and LV feeders. The most common form of load monitoring is via the installation of 'Maximum Demand Indicators' on the larger distribution transformers, which are read bi-annually. Historically there have not been large changes to the 'After Diversity Maximum Demand' (ADMD) of residential households and therefore this relatively simple and low cost approach has served the distribution network well.

However, if not correctly managed, the arrival of EV's may change the ADMD of households. A fast uptake of EVs causing LV network constraints could be problematical for distribution network owners because of the wide scale nature of the LV network and the construction constraints and cost implications that may eventuate.

Modelling of a Distribution Network

Information supplied by Orion characterised the relevant network sections from the grid exit point down to the sample low voltage feeders and contained line impedance parameters and lengths, as well as load connection points with typical loads connected during peak load times. Two sample feeder networks were investigated and are illustrated in Figure 13:

- A typical overhead line feeder with 75 loads, each representing one urban dwelling with an average 2-3 kW peak load (pf = 0.97).

- A high-density residential underground network with 12 multiple dwelling loads of 10-15kW peak load.

(a) overhead lines
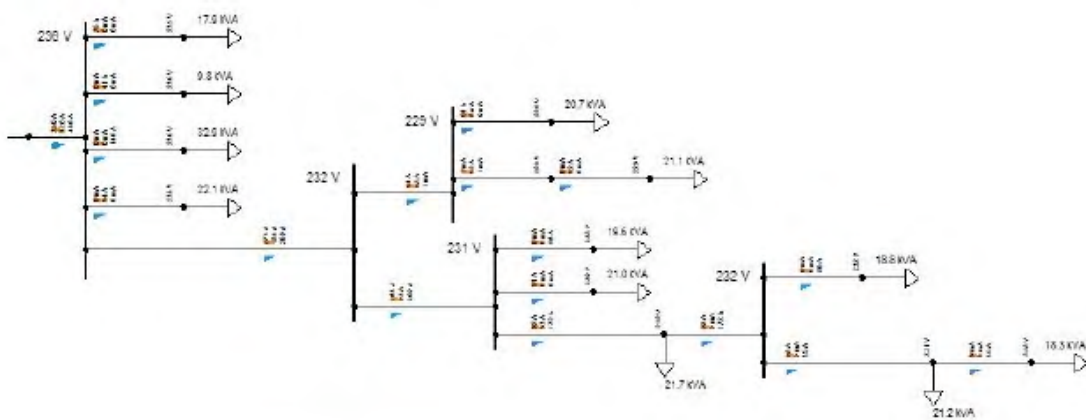
(b) underground cables

Figure 13: Typical Low Voltage Feeders

5.2 Electric Vehicle Charger Model

As electric vehicle chargers are not generally available to measure the requisite input data for this study such as harmonic currents, a harmonic model of an EV charger was created by studying similar non-EV chargers and the relevant standards. 5 kW chargers were used as the basis for the study as they are compatible with existing household applications[45] and necessitate only minor wiring modification. Power quality effects will be greater for larger chargers, which might be favoured by electricity suppliers for load control purposes.

It is likely that in mass production of electric vehicle chargers, cost of production will be important and therefore only require minimum compatibility with standards. Internationally, the IEC 61000-3-2 Class A standard for harmonic current emission limits for equipment connected at LV with input current ≤16 A per phase is often required and potentially could be applied to EV charger equipment.

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[45] LV network design by Orion requires sufficient capacity for 5kVA ADMD per household and charging at night with a background load of 2kVA per household and some diversity of EV chargers, 5kVA appears achievable. We note that there are a number of EV's becoming available with 15-20A chargers (3.5-4.5kVA chargers).

Consequently, assumptions used in this analysis include:

- The harmonic current limits specified in the IEC 61000-3-2 Class A standard are used for the EV charger model[46].

- To determine the effects of a poorer current wave shape, the effects of EV chargers with twice the IEC standard's current limits were determined. Harmonic currents injected for the modelled 5kW EV charger are shown in Table 3.

- It is not known what harmonic diversity EV chargers will have, but it is likely that it will be low[47]. For this study, some diversity for each harmonic was created by the harmonic angles for the first installed EV charger being set to 0°, the harmonic angles of the second charger being set to 38° and the third charger being set to 76°. This pattern was repeated for the following EV charger installations, allowing for some EV charger harmonic cancellation as would be expected in a real network.

n	IEC 61000-3-2 Class A limits (Amps)	IEC 61000-3-2 Class A limits for 5kW charger (%)	Twice the IEC 61000-3-2 Class A limits for 5kW charger (%)
3	2.3	10.6	21.2
5	1.14	5.3	10.6
7	0.77	3.5	7
9	0.4	1.8	3.6
11	0.33	1.5	3
13	0.21	1	2
15	0.15	0.7	1.4
17	0.13	0.6	1.2

Table 3: Injected harmonic currents (%) for the modelled 5kW EV charger.

- EV chargers will be operating for multiple hours, and therefore simultaneously for certain times of the day such as evenings and nights. It is assumed EV chargers are operating simultaneously and mostly at full power until the EV battery is full.

- Only the effects of simultaneously operating EV chargers are calculated. For instance, the calculations for 10 operating chargers may represent a total of 10 EV charger installations in the feeder all operating at the same time, or a 20 EV charger installation situation where only 50% of the chargers typically operate at any one time.

5.3 Harmonic Effects

Harmonic voltages were calculated at the point of common coupling to demonstrate the effect of adding EV chargers one by one to the modelled networks. The chargers were attached to the feeders in a scattered fashion, while trying to keep an approximate balance across the three phases. This is likely to be how EV chargers will be installed in the future. To illustrate the difference in effect between peak and low load situations, additional harmonic calculations were performed when each averaged non-EV load was decreased to 10% of its original peak load value. EV charger loads remained at 5kW.

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[46] Measurements taken by the study authors of similar equipment (other battery chargers, heat pumps, rectifiers) often show similar harmonic profiles and support the choice of harmonic values used in this study.

[47] Harmonic diversity is the spread of vector angles that each harmonic has. Often power electronic loads have similar harmonic angles (low diversity), resulting in the addition of harmonic magnitudes rather than partially or totally cancelling.

Figure 14 shows the percentage increase in total harmonic distortion (THD) as EV chargers are added. For IEC61000-3-2 Class A limit chargers, increases in THD of up to 0.9% could be expected with an overhead line feeder in a low load density environment for the first 15 charger installations (out of a total of 75 normal loads or dwellings on that feeder). The expected increases in voltage THD are slightly lower for underground cables in a high load density environment (figure 15). Typical urban voltage THD levels can presently range from 2-3%, and so an increase of an additional 1% due to EV chargers would be moderately significant. The present NZECP36 harmonic limitations standard limits voltage THD to a maximum of 5% at the point of common coupling.
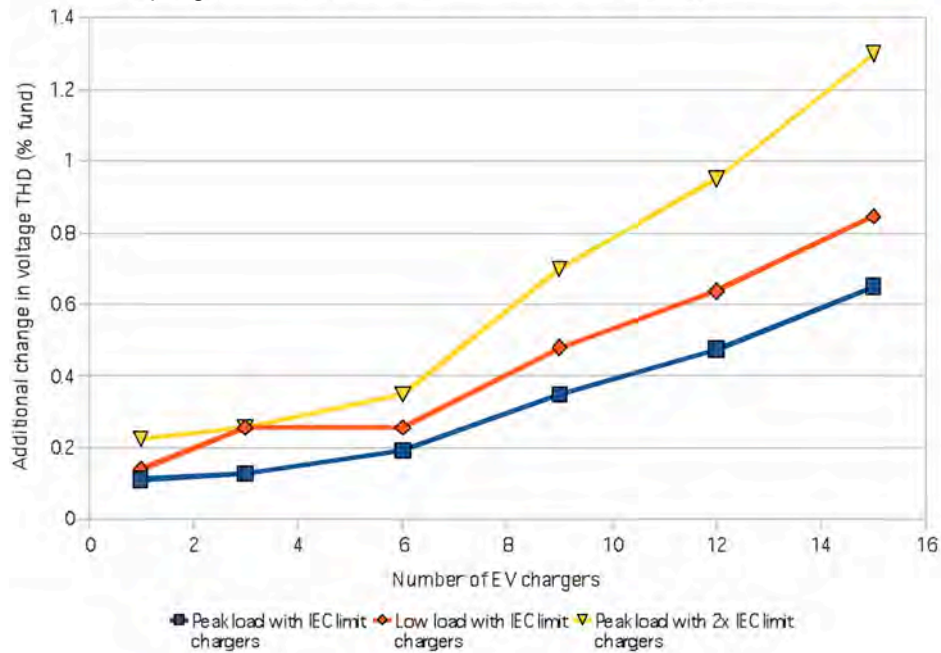

Figure 14: Additional change (% of fund.) in voltage THD at the PCC as EV chargers are added to feeder consisting of overhead lines in a low load density environment
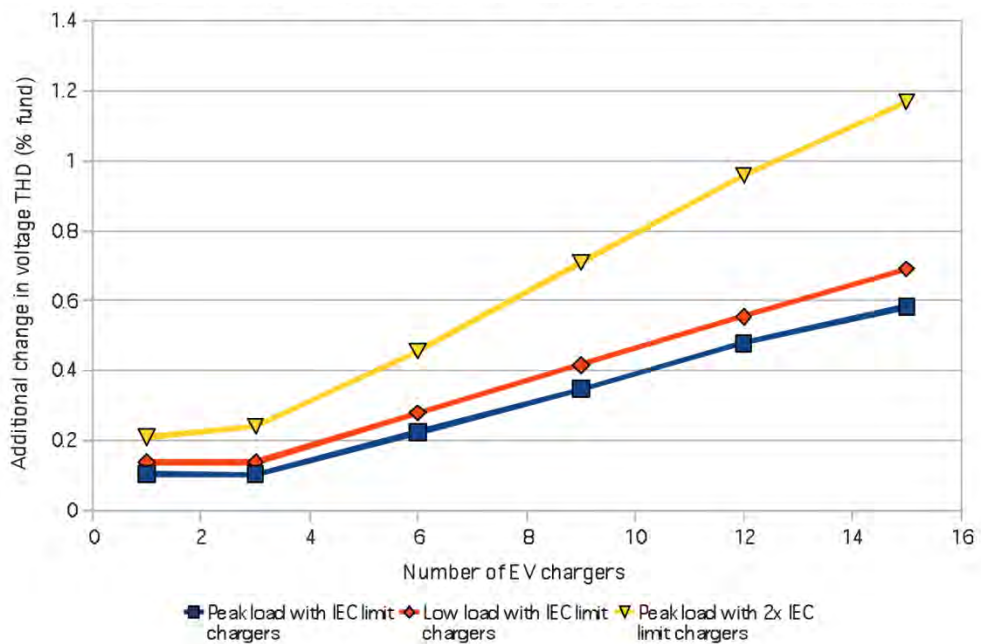

Figure 15: Additional change (% of fund.) in voltage THD at the PCC as EV chargers are added to feeder consisting of underground cables in a high load density environment

An increase in the 5th harmonic voltage of 0.4% can be expected with fifteen 5 kW IEC61000-3-2 Class A limit chargers operating simultaneously on an overhead feeder (Figure 16). This compares with the present NZECP36 standard, which limits 5th harmonic voltage to 4% at the point of common coupling. As with voltage THD, this effect will be somewhat lower in the higher density underground feeder configuration (figure 17) but can be significantly higher if the IEC 61000-3-2 Class A standard is exceeded.
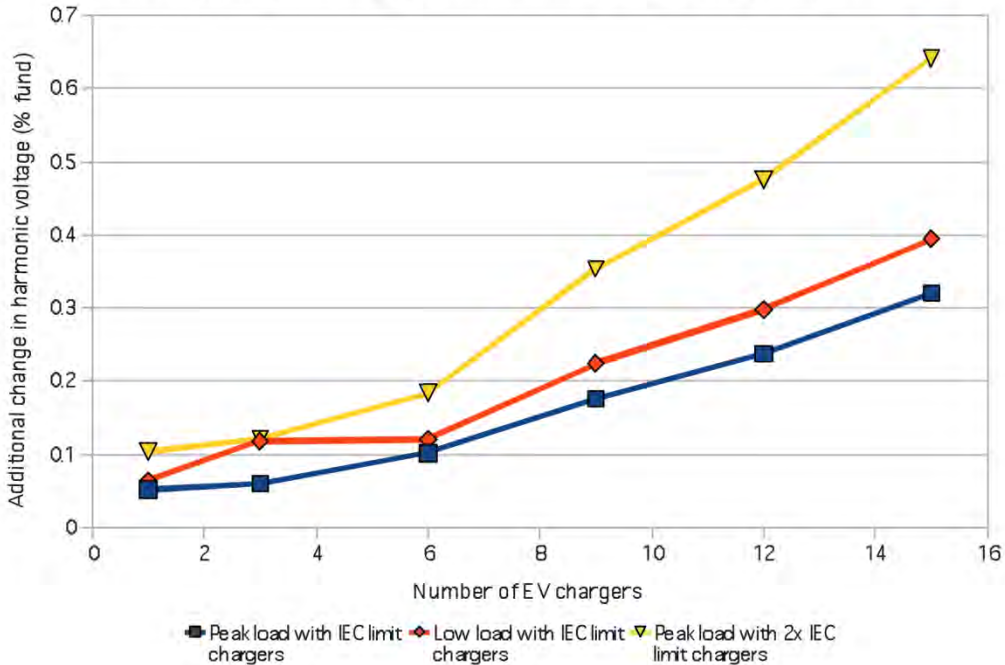

Figure 16: Additional change (% of fund.) in 5th harmonic voltage at the PCC as EV chargers are added to feeder consisting of overhead lines in a low load density environment
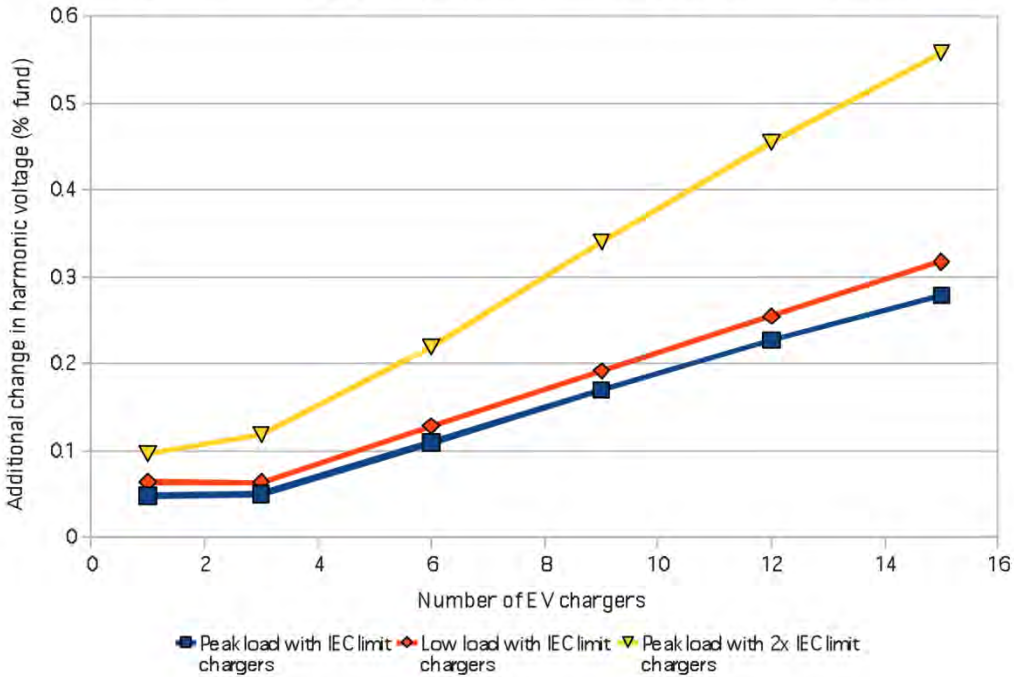

Figure 17: Additional change (% of fund.) in 5th harmonic voltage at the PCC as EV chargers are added to feeder consisting of underground cables in a high load density environment

Widespread adoption of electric vehicles has the potential to significantly affect power quality as demonstrated in this initial study of harmonic effects:

- Other new residential appliances that will be connected in the future are also likely to increase harmonic voltage levels, therefore requiring EV chargers to not solely take the remainder of the gap between present harmonic voltage levels and the NZECP36 limits.

- If EV chargers are hypothetically allocated a 2% share in voltage THD headroom (out of the maximum 5% limit) at the PCC, then a limit of approximately 30 out of 75 (40%) houses on that feeder could use their EV charger at any one time.

- To allow 80% of houses to simultaneously use their EV charger would require harmonic current limits that are lower than half the levels specified by IEC61000-3-2 Class A. This would require a 5kW EV charger to have a current THD of less than approximately 7%.

- The impact could worsen rapidly if EV chargers have lower harmonic diversity than assumed in the study or exceed the IEC 61000-3-2 Class A standard.

While the first few (up to 5-6) EV chargers to be installed are unlikely to have a significant impact on the overhead or underground lines distribution networks, the NZECP36 limits could be exceeded as additional EV chargers are installed. To prevent harmonic voltage limits being exceeded, options could include specifying suitable harmonic current limits for EV chargers, upgrading distribution lines (which is likely to be expensive) or installation of network harmonic filters at PCC (also quite expensive). Consideration should also be given to changing the harmonic voltage limits specified by NZECP36.

5.4 Voltage Drop Effects and Network Load

To see the effect on voltage drop from adding EV chargers to the network along the overhead and underground feeders (shown in Figure 13), load flows were calculated at 50 Hz in SinCal software as 5 kW EV chargers (PF=0.97) were connected in a scattered fashion across each feeder. Each feeder had a total of 75 dwellings, to which 75 EV chargers were progressively attached. These calculations were performed when all dwellings had a normal load of 2 kW (PF=0.97). This is an approximate winter early morning (1am-4am) load value for the Orion network. It is likely that most EV charging will be performed around this time.

Figure 18 shows the voltage drop (difference between the PCC and bottom end of the feeder, A in Figure 13) for both overhead line and underground cable systems. While the voltage drop on both feeders trends upwards as EV chargers are connected, it is only the voltage drop on the overhead lines feeder that is significant. The small variation in voltage drop around the average (the curved lines in Figure 18) is mostly due to the random nature of the EV charger connection locations and some minor load unbalance. The steeper increase in each of the averages is likely due to feeder topology and the EV chargers being constant power devices.
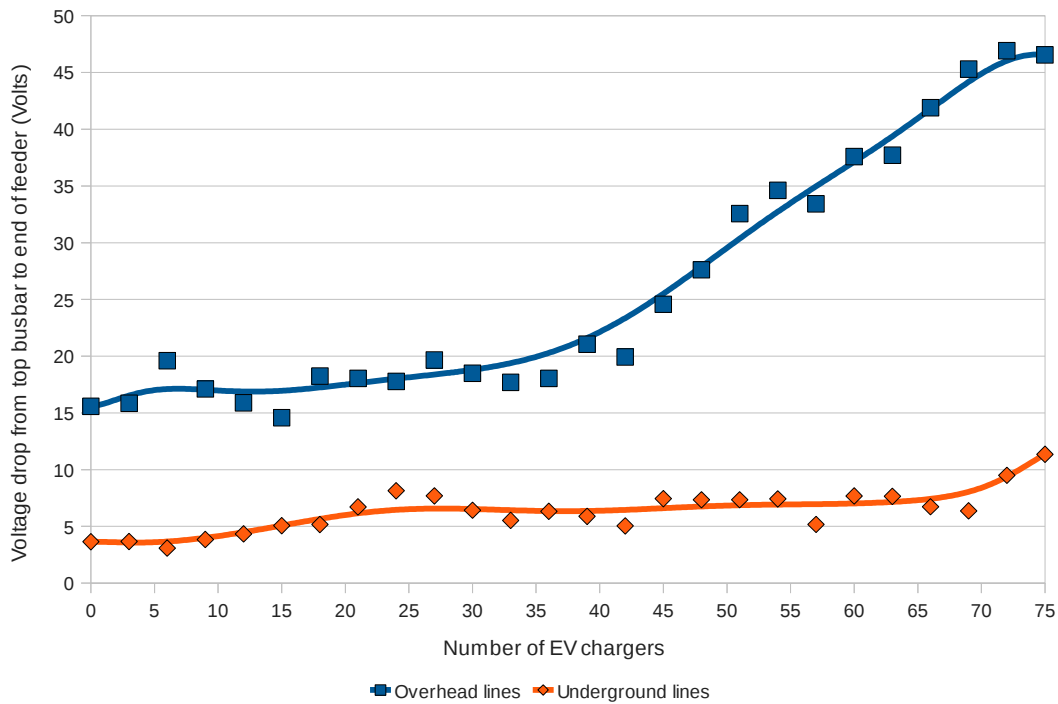
Figure 18: Single phase to neutral voltage drop between top and bottom of feeders

For this feeder topology, it is very likely that voltage drop will not be of concern for the first 50% of EV charger installations (all simultaneously operating). However, it is likely that the voltage drop in the overhead lines will exceed NZ's 230 ±6% Volts requirements at approximately 45-50 installed EV chargers (~60%). Voltage drop is not likely to be a problem for high load density environments connected by underground cables. Different network topologies with overhead lines are likely to produce some variation in voltage drop between the PCC and the end of the feeder. These different topologies include feeders that only consist of a long line with no branches, and feeders with non-uniform distribution of the loads along it. Further investigation could look at a wider variety of feeder topologies.

Consideration of feeder limitations due to the ratings of the transformer, lines and other equipment was not taken into account. While performing the voltage drop calculations, it was noted that the transformer at the PCC became overloaded with more than 25 EV chargers connected.

Variation in voltage drop was notable with load unbalance across the three phases. Further investigation of unbalance effects with the installation of EV chargers is also recommended.

6 Effects of Electric Vehicle Charging on Power System Development

The following discussion considers the possible effects on the generation system and high voltage transmission grid of a number of scenarios for the uptake of electric vehicles. Some concerns that are commonly raised are "How much additional electricity will be required?", "Where will this electricity for electric vehicles come from?" and "Will additional high voltage transmission lines be required?"

Studies have also been carried out to test the effect of excluding the super peak of 35 hours per year from supply of the extra energy, i.e. the charging that is not done during off peak periods is excluded from the super peak for these cases. This small number of extreme peak hours can have a significant impact on power system investment – transmission system capacity is driven to a large extent by the need to meet peak loads, and this peak is also an important factor in determining the installed capacity needed by the generation system.

6.1 Generation System Analysis

Electricity system modelling has been carried out using the Electricity Commission's Generation Expansion Planning Model (GEM). GEM is used by the Commission and Transpower to determine possible generation system expansion paths, when analysing transmission grid upgrades. It has also been used by the Ministry of Economic Development in preparing scenarios of future energy consumption in New Zealand for the Energy Outlook studies.

The analysis presented here has been based on the Energy Outlook Reference Scenario, prepared by the Ministry of Economic Development. The Ministry considered the overall national energy supply situation, making use of their SADEM model, but with more detailed modelling of the electricity system carried out using GEM. Because the results of their studies are readily available, and carried out as part of an overall national energy balance study, the Energy Outlook Reference Scenario is an appropriate scenario for use here. A copy of the input data used for that study has been made available by the Ministry, and forms the basis of the GEM model inputs used.

The period modelled for this study is the 30 years from 1 January 2010 to 31 December 2039. Details of the GEM model are given in Appendix 1.

6.2 Key Assumptions from the Energy Outlook Reference Case
The following key assumptions were made by the Ministry of Economic Development in the preparation of their Energy Outlook Reference Scenario:

- GDP growth follows the projections produced by Treasury; in the short term, from the Budget and Economic and Fiscal Update 2009, and in the longer term, from the Long Term Fiscal Model where rates trend down towards the long-run labour productivity rate of 1.5%.

- Exchange rates to 2013 are based on Treasury's updated forecast. For the period 2014 to 2020, exchange rates trend towards the long-term rate of 0.6 US$/NZ$ and remain at this rate indefinitely.

- Oil prices are assumed to follow the NYMEX futures price in the near term, trending towards the IEA's World Energy Outlook mid-case projection of US$120/bbl by 2030.

- Gas prices are assumed to rise to $8.50 / GJ by 2020. Post 2020, tightening gas supply sees gas prices begin to rise to the MED's Energy Outlook values for the opportunity cost of electricity of approximately $13/GJ (including emissions pricing) by 2035 (See Figure 17). 65 PJ of gas are available per annum for electricity generation. Consequently no increase in the capacity of base load gas fired generation is possible.

- An emissions price of $25 per tonne of carbon dioxide is included.

- Two Huntly coal units are switched to dry year reserve plant in 2015 and 2017 respectively, and finally decommission in 2028 and 2030. The remaining units decommissioning in 2019 and 2021

- Existing base load gas plant at Stratford and Otahuhu is decommissioned in 2025 and 2030 respectively but can be replaced by new base load plants.

- Wholesale electricity prices increase approximately 1.6% per annum above the rate of inflation. Electricity demand grows at 1.5% per annum, down from a historical rate of 1.8%

- A 7% real discount rate has been used for this study.
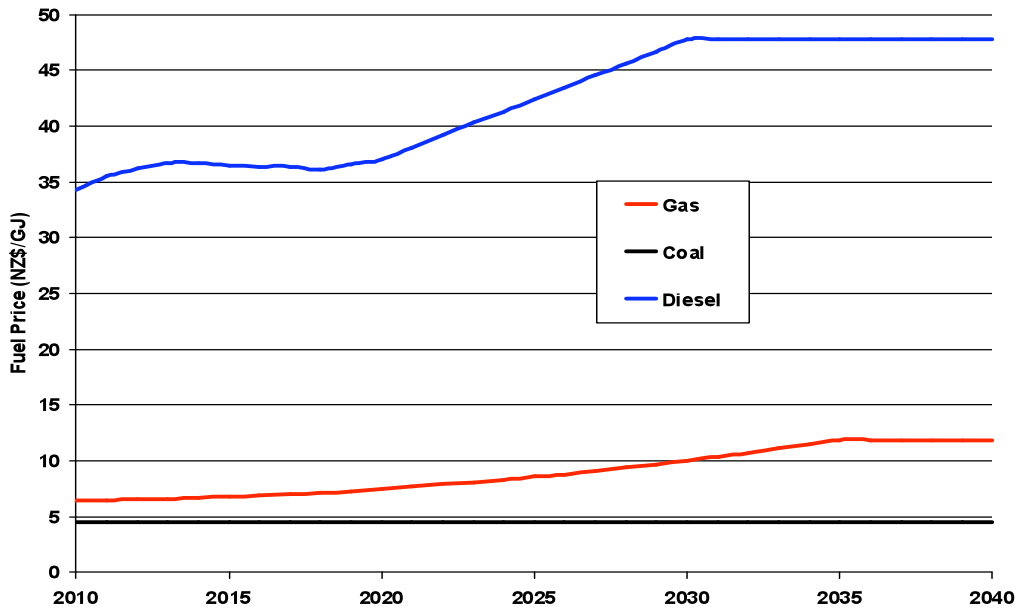
Figure 19: Fuel Prices (Excluding CO$_2$ Emissions Charges)

6.3 Representation of Load and Time

Modelling each hour of the thirty-year study period is impractical as solution times would be extremely long. To make the problem tractable, time is divided into three-month periods. To enable the modelling of load variability within each of these periods, the load is represented by nine categories, each representing some proportion of the month, as shown in Table 4.

Load block 1 represents the highest system load for each three-month period, with the successive blocks representing lower loads. Load block 1 represents the highest 0.1% percent of loads for the period. Load block 2 represents the next highest 0.3% of loads, etc. This compact representation of load enables the modelling of the system for a three-month period to be reduced from 2190 hours down to just nine load blocks.

Load Block	1	2	3	4	5	6	7	8	9
Proportion of period	0.001	0.003	0.01685	0.05055	0.05358	0.16073	0.3214	0.2857	0.1072

Table 4: Load block sizes, as used in Generation Expansion Planning Model

For each three-month period, the optimal system dispatch must be calculated in addition to the selection of new plants to commission and existing plants to decommission. The optimal dispatch decision-making involves minimising the sum of thermal plant fuel costs including CO_2 emissions charges, the variable operation and maintenance costs incurred by all plants, and the cost of energy shortfalls, subject to a variety of constraints.

A further simplification to make the optimisation problem tractable is that the commissioning of new plant is assumed to occur only at the beginning of each year.

Load to be satisfied within GEM is defined as the total generation required, excluding losses on the inter island HVDC link. Load forecasts have been prepared as the off-takes occurring from the high voltage transmission grid. Losses on the grid are not represented explicitly within GEM, so the loads in each island have been increased by 3.68% in the North Island and 5.34% in the South Island to take these into account.

Figure 20 shows the total annual baseline load forecast from the MED's Energy Outlook Reference Scenario. The additional load per year required for electric vehicle battery charging is also shown for each of the four uptake scenarios investigated.

It is clear that even with a very high uptake of electric vehicles, the total load due to vehicle charging is only a very modest proportion of the total system load, little more than 8% in the most extreme scenario. By way of comparison, the mean annual potential output from the Benmore hydro station is approximately 2,380 GWh – even an extremely optimistic scenario for the uptake of electric vehicles would require two additional hydro stations equivalent to Benmore.

In addition to the energy required by vehicle charging, the effect on system load at any instant is important. Figure 21 shows the increasing instantaneous loads for off peak and peak periods for the 80% uptake scenario. 85% of charging is assumed to be done in shoulder and off-peak periods, with the remainder spread uniformly over the day, but excluding the short duration super peak periods. By 2040, off peak loads will be increased by 700 MW. By this time, total installed generation capacity would be almost 25,000 MW, in the optimal development plan calculated by the GEM model.
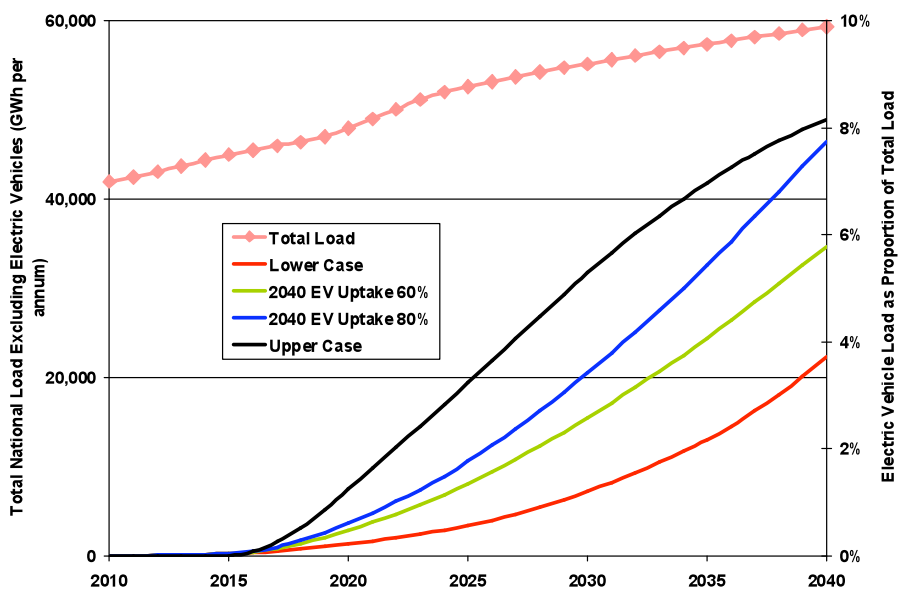

Figure 20: Baseline Load Forecast and Percentage of Total Load Required for Electric Vehicle Charging
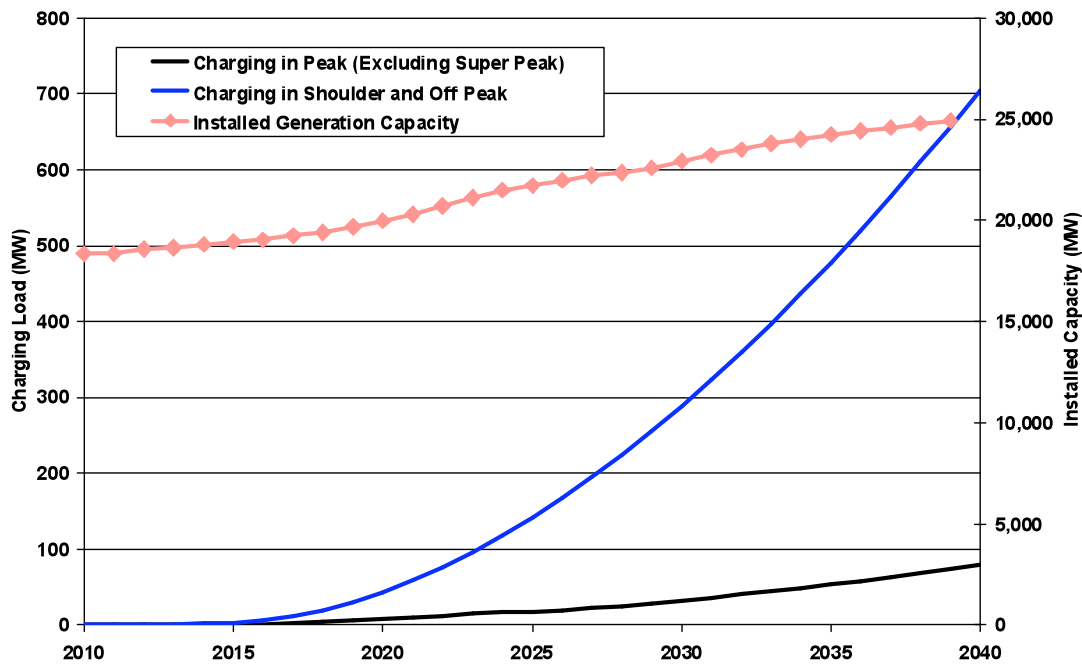
Figure 21: Increased Peak and Off Peak Load due to Vehicle Charging: 80% Uptake Scenario[48]

6.4 Modelling Electric Vehicle Charging Loads

Given that electricity loads are represented within the GEM model as a load duration curve, consisting of nine load blocks, some proportion of the electric vehicle charging load must be allocated in some way to each of these blocks.

If charging was assumed to occur uniformly over each day, then a constant MW load would be added to each load block. This assumption is equivalent to charging occurring at completely random times. The impact on the power system would be considerable, because the peak loads would be increased. This increase would require additional generation and transmission capacity to be constructed. This mode of charging is investigated in the "Flat" charging option.

An alternative assumption might be that all charging occurs during shoulder and off-peak times – the three lowest load blocks, which account for over 71% of each quarterly time step. This option would not increase peaking generation requirements, and would enable better utilization of generation plant by flattening the load shape. Utilisation of lower cost base load plant would be improved, as would the use of non-schedulable generation, such as generation from wind and marine sources.

From the discussion in Section 4, it is probable that a significant proportion of charging can be carried out during off peak periods. This off peak charging is modelled as being spread uniformly over the three lowest load blocks. Given that these load blocks represent 71% of the period, this will include nights, weekends, and some week day daytime periods. Even more economical charging may be possible with improved control of the timing at which charging occurs, which could even be equivalent to allocating the charging load over the 39% of time in the two lowest load blocks.

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[48] 85% of charging during super peak periods, no charging during super peak.

The remaining charging energy which is not supplied during the off-peak hours has been allocated in two alternative ways:

- Spread uniformly over all hours of each three-month period, i.e. assuming that this charging occurs completely randomly.

- Spread uniformly over all hours of the period, but not in the super peak consisting of the highest load hours, 0.4% of the total time. This is equivalent to excluding charging from the peak 35 hours of the year.

6.5 Typical Load Patterns

Figure 22 shows the large variability in loads that exist each day, providing opportunities for a significant controllable load to be supplied without increasing peak demands. Potentially the utilisation of existing base load generating plant can also be improved by scheduling charging loads over the lower load periods.

Half hourly loads for a one-week period are shown for the Penrose and Islington exit points. The first two days are Saturday and Sunday, which have lower loads due to lower commercial and industrial use. Very marked variations over each day are present with weekday minimum loads at Penrose less than half that at the peak. At Islington, the winter minimum is often a little more than half the peak load. The increasing peak at Islington as the week passes suggests that colder weather was experienced later in that week.
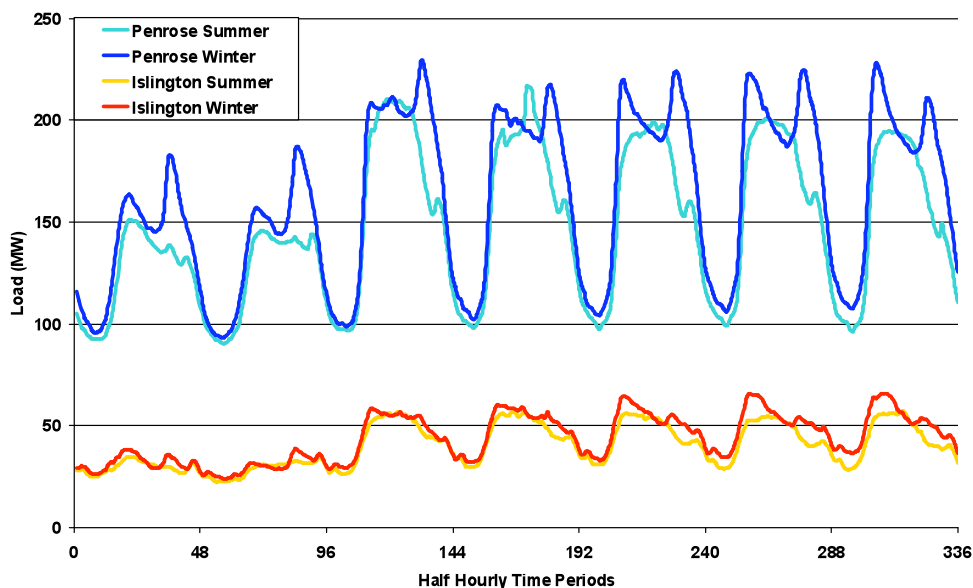
Figure 22: Typical summer and winter week loads at Penrose and Islington

In winter, peak loads each morning are approximately 10 hours after the preceding day's evening peak (Figures 7 and 22), leading to the observation that off-peak vehicle charging can be spread over a 10 hour period, without increasing demand beyond the peak levels. In weekends, additional time is available between successive peaks. Most days there is a dip in load part way through the day, which offers another opportunity for vehicle charging to smooth the load shape. In summer, the load in the sample periods tends to be a little smoother, but the general shape of load is similar, showing that there are opportunities for off peak charging loads in summer and winter in both islands.

6.6 GEM Model Results

Several stages are involved in the solution process followed by the GEM model. The first stage optimises for the commissioning dates of plant assuming that inflows to the hydro system are at 97% of mean. This proportion of mean inflows in the GEM model has been found to give results that are close to optimal when tested using a stochastic model, i.e. a model fully accounting for uncertain inflows. This is referred to as the "timing" stage. Next, a "re-optimisation" phase is carried out using hydro system inflow data for a low inflows year. In this second stage, the results of the timing stage are fixed, but additional dry year backup plants can be added, if this results in lower system operating costs. Finally, in a third phase, the "dispatch" phase, the plant development program found in the re-optimisation phase is simulated using the record of 72 historical inflow sequences for the hydro system. The average results from these 72 simulations of the dispatch phase are used in this report.

The dispatch modelling carried out by GEM is simplified to allow a solution to be found within a reasonable time. A more detailed dispatch model, such as the Stochastic Dual Dynamic Programming model (SDDP) developed by Power Systems Research Inc would give more realistic results. The optimal commissioning schedule prepared using GEM can be analysed in more detail by SDDP, taking into account a wider range of power system features.

6.6.1 Cost of Generation for Vehicle Charging Loads

The additional system costs considered are total generation costs, those for capital, fixed and variable operating and maintenance costs, carbon emission charges and fuel purchases, and are expressed as the levelised cost of supply which gives a useful summary of the costs applying over several years[49].

Table 5 (below) shows that the cost of supply increases with the volume of energy required, from the lower electric vehicle uptake scenario, through the 60% and 80% scenarios to the upper scenario. On the other hand, costs decrease as load is moved out of the peak period, from uniformly distributed charging, through 50% charging at off peak and shoulder periods, to 85% of charging performed during the off-peak and shoulder periods. The final line of Table 5 shows how additional load control would reduce costs further. For this option, controls would restrict the remaining 15% of charging which is not concentrated in the off peak periods so that is would not occur during the super peak 35 hours of the year, resulting in further reduction in costs for three of the four electric vehicle uptake scenarios.

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[49] The levelised cost is calculated by present worthing all additional costs for the electric vehicle scenario above those for the base case with no electric vehicles, and dividing by the present worthed total energy supplied for vehicle charging over the entire study period. This is likely to give a more comprehensive estimate of costs than would the use of a long run marginal cost, or short run marginal costs from a dispatch model.

Scenario	Lower	60%	80%	Upper
Total energy for vehicle charging loads over 40 year period (GWh)	16,300	31,300	41,500	57,800
Constant charging (c/kWh)	10.79	10.85	11.54	11.32
50% of load off peak or shoulder periods, 50% uniformly distributed, but excluding super peak hours per year (c/kWh)	10.05	9.49	10.13	9.97
85% of load off peak or shoulder periods, 15% uniformly distributed (c/kWh)	8.28	9.23	9.34	9.77
85% of load off peak or shoulder periods, 15% uniformly distributed, but excluding super peak hours per year (c/kWh)	8.13	9.08	9.48	9.6

Table 5: Levelised Cost of Generation for Electric Vehicle Charging[50]

6.6.2 New Generation Plant Development Program

Table 6 shows the additional installed generation capacity required by 2039 for two possible vehicle charging patterns:

- uniformly distributed vehicle charging load
- 85% of charging in shoulder and off-peak with the remaining 15% uniformly distributed but excluding super peak period

The capacity shown in Table 6 is that required in addition to the new capacity that would be installed in the base case (no extra vehicle charging load). It also shows the additional load that would apply if all charging was carried out uniformly throughout each day. Additional installed capacity required as in Table 5 is approximately twice as much as the average load, expressed in MW terms. For example, for the Upper Scenario, 1,200 MW of additional installed capacity is required by 2039 to supply a load which has been increased by only 558 MW, on average. A greater amount of new generation capacity is required because the full effect of that capacity is not necessarily available at the peak period. An assumption is made within the GEM model that varying proportions of each type of capacity will be available at the peak time.

Scenario	Lower	60%	80%	Upper
Charging load distributed uniformly	450	870	1,140	1,200
85% of load off peak or shoulder periods, 15% uniformly distributed, but excluding super peak hours	433	644	777	825
Increase in peak load in 2039 due to uniformly distributed charging				
Additional load	235	380	510	558

Table 6: Additional installed generation capacity required by 2039 (MW)

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[50] Off peak and shoulder periods consist of 71% of hours. Super peak consists of 35 hours per year.

Figure 23 shows how additional installed capacity requirements evolve over the study period, for cases with uniformly distributed charging, and the case with 85% shoulder and off peak, which also avoids the super peak period. Clearly in all except the lowest electric vehicle uptake scenario a considerable saving in peak generation system capacity can be achieved by avoiding charging during the super peak period.
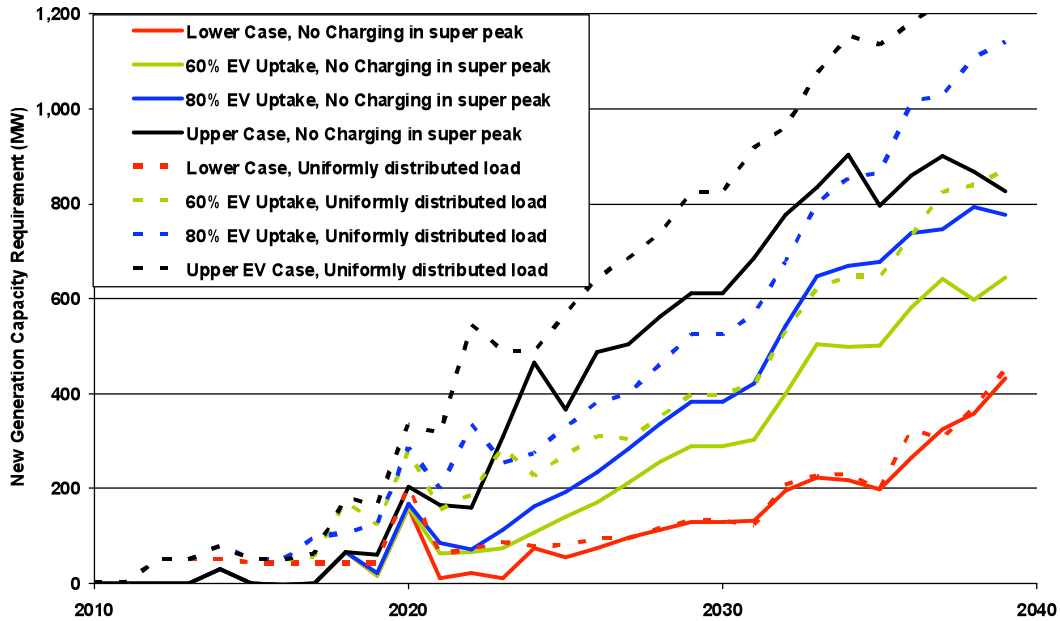
Figure 23: Additional Installed Capacity Required for Vehicle Charging

To examine when electric vehicle charging might begin to have an impact on the power system, some details for the 80% uptake scenario are shown in Figure 24 for the forthcoming 16 years. By 2025, almost 400,000 vehicles are included in the national fleet. Additional generation capacity requirements calculated by GEM reach approximately 200 MW at about this time, assuming no charging during the super peaks.
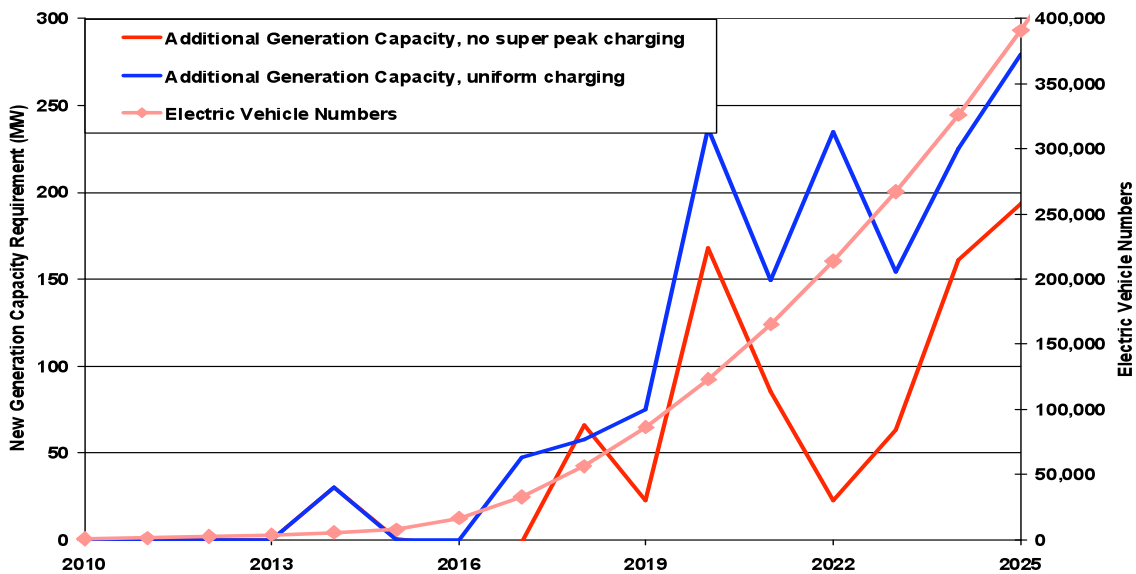
Figure 24: Additional Installed Capacity Required: 80% Uptake Scenario

Details of the additional installed capacity of each type added to the system over this period are shown in Table 7. It shows that demand side management capacity beyond that required in the base case is added to the system over the period 2015 to 2019 if there is no charging in super peak hours. In 2020, however, both the base case and the electric vehicle scenario have the same total amount of demand side management, indicated by the zero entry. Therefore the electric vehicle scenario has advanced the use of demand side management to a varying extent in each of these years. For fossil fuelled peakers, on the other hand, construction of 150 MW of capacity is delayed over the four years from 2014 to 2017 by the addition of electric vehicle charging loads. Both scenarios have the same installed capacity of fossil fuelled peakers in 2018. The table also shows that even for the worst case charging option - uniformly spread charging loads – a significant shift occurs from fossil fuelled peakers to geothermal plant, over the same period.

No Charging in Super Peak Hours (MW)												
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Demand side management	0	0	27	63	48	15	15	0	-51	22	0	0
Fossil Fuelled peakers	0	-150	-150	-150	-150	0	0	0	0	-200	-50	-50
Geothermal	0	180	140	100	117	67	0	0	0	0	0	0
Hydro	0	0	-17	-17	-16	-16	7.55	168	-41	-23	113	16
Wind	0	0	0	0	0	0	0	0	178	224	0	195
Total	0	30	1	-3	-2	66	23	168	85	23	63	161
Uniformly Allocated Charging (MW)												
Demand side management	0	0	29	66	44	15	15	17	-35	22	0	0
Fossil Fuelled peakers	0	-150	-150	-150	50	50	50	50	50	-150	0	0
Geothermal	0	180	140	100	-30	0	0	0	0	0	0	0
Hydro	0	0	-17	-17	-17	-7.6	9.5	170	-20	-55	-36	16
Wind	0	0	0	0	0	0	0	0	154	418	191	209
Total	0	30	2	0	47	58	75	237	149	235	154	225

Table 7: Additional New Capacity for 80% Uptake Scenario

The most significant change in the development program due to vehicle charging loads is the construction of geothermal plant earlier in the study period, in place of gas and diesel fired peaking plant. Later in the period shown in this table, some hydro and wind generation is construction is brought forward and further delays occur for fossil fuelled peakers. These changes are consistent with the addition of loads at off peak and shoulder periods, flattening the overall load shape. This results in the impacts on the generation system being less than might otherwise be expected.

Figure 25 shows changes in installed generation capacity, relative to the base case, for the 80% uptake scenario, with 85% of charging carried out during shoulder and off-peak periods, no charging during super peak hours. In the long term there is a trend for a reduction in fossil fuelled peaking plant but significant additional wind capacity. A smaller effect is observed in some earlier construction of biomass, hydro and marine power sources. The addition of the controllable charging load improves the system load factor, enabling additional non-schedulable generation to be added, i.e. wind and marine.
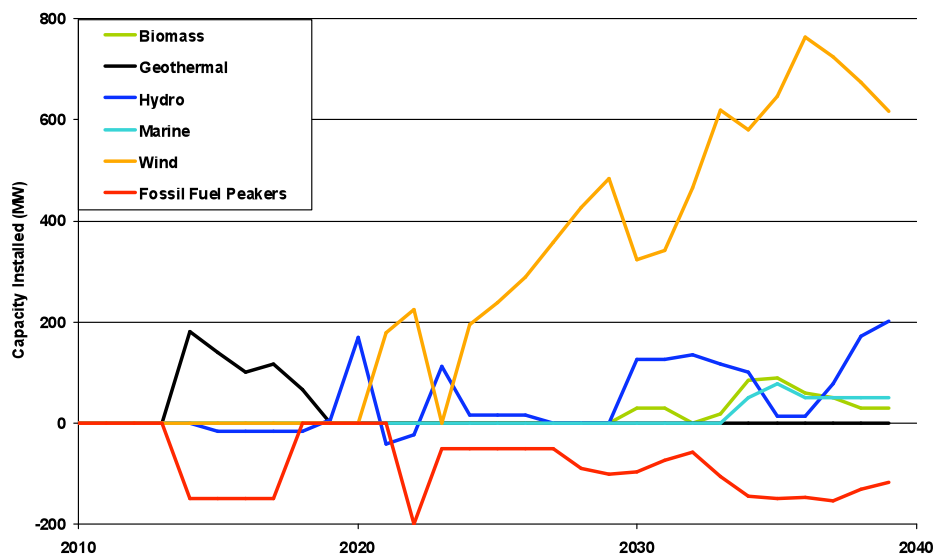

Figure 25: Change in Installed Capacity Relative to Base Case
(80% Uptake Scenario, 85% shoulder/off peak charging, no super peak charging)

7 Vehicle – Grid Interface

Technology for charging electric vehicles in private and public locations is already available and progress has been made in instituting standards for electrical connections between vehicles and the electricity supply network. Coulomb Technologies in the USA and Elektromotive in Britain have developed packaged systems combining plug-in electric vehicle supply equipment with electricity metering, billing and security features. Payment can be made in a variety of ways including prepaid electronic key, proprietary access card and smart credit or debit cards.

The Society of Automotive Engineers has issued a standard for electric vehicles couplers[51] for loads up to 16.8 kW which has been adopted by the major vehicle manufacturers. SAE specifies three basic charge levels: Level 1 has sufficiently low power inputs so that all charging equipment is typically installed on the vehicle allowing the vehicle to be plugged directly into existing household electric circuits; Level 2 employs special electrical supply equipment installed in households by an electrician to provide a higher level of safety up to currents of 80A and includes the favoured 4 to 5 kW charging rate; and Level 3 for "Fast Charging" up to 150 kW in commercial and public applications requiring three phase supply. Public and private electric supply equipment presently available falls in the Level 1 and 2 ranges with Level 3 technology under development.

Vehicle charging technology has kept pace with the development of electric vehicles and, unlike battery technology, is unlikely to present a constraint on the development of the electric vehicle mass market. Technology used for payment, metering, communications and control is current today and will doubtless be improved upon as the market expands over time. Limitations to rates of charging are imposed by household and distribution network capacity constraints and battery technology rather than the chargers themselves.

There is currently considerable emphasis on "smart charging" in the development of electric vehicle supply equipment. This provides an interaction between the electric vehicle and the electricity supply system beyond simple charging and potentially includes some of the following features:

- Time of use tariffs
- Electricity supply system reserve and controllable load
- Load shaping to flatten load profile or maximize renewable generation
- Electric vehicle batteries as storage to supply back to the home or grid.

Benefits from managing vehicle charging loads are discussed and quantified in Section 6. The following section discusses some of the means of controlling vehicle charging and the provision of electricity supply system reserves. A range of possibilities for the provision of reserves would exist if electric vehicle chargers incorporated some innovative features, and these were to be combined with smart metering. To encourage the implementation of these potential power system benefits, electric vehicle charging supplies would need to be metered separately from other electricity consumption. This would enable consumers to financially benefit if some special characteristics were to be incorporated into vehicle battery chargers.

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[51] SAE Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler, J1772, issued January 2010

7.1 Controlling Electric Vehicle Charging

The traditional form of load control in New Zealand has been the ripple control system. Ripple control of domestic hot water heating continues to be used by some lines companies to reduce peak loads. This system involves injecting a signal at a specific frequency that is detected by receivers at the customers' switchboards. A relay turns the controlled supply on or off in response to the signal. By using a number of different frequencies, it is possible to turn off just a proportion of the total controllable load. Lines companies use this form of load control to reduce the maximum total load at the points on Transpower's high voltage grid from which the company's customers are supplied. This reduces the lines company costs as Transpower bills them according to peak power requirements. The peak determines the investment Transpower must make to provide supply.

When the peak load period passes, hot water heating is restored, and the consumption of those heaters increases as they recover from the period of the cut. As the total energy consumed is not significantly affected, this is not an energy rationing mechanism. Ripple controls could be used to control the times at which electric vehicle chargers are disconnected to avoid charging over peaks. Control units can also be fitted at an individual power outlet, and so could be used as the means of managing charging loads until more sophisticated controls become available.

Ripple controls have not previously been used to provide rapid reductions in load during a system incident for example. This is because the process of generating the required ripple signal and the switching of loads is too slow.

Whilst ripple control provides a potential solution for managing EV charging over the network peaks and also coordinating charging during the night, it may be better to install some control capability within the EV charger (or a NZ add-on to the charger). In the absence of two-way communications between the EV vehicle residence and the network company, the following approach would realise significant benefits for NZ.

The night rate load on the network is at a minimum around 4am and if all EV charging could be centred on 4am, then the need for two way communication or ripple could be avoided for moderate uptake levels of EV's. The EV charger would need to be able to determine the amount of top up required and start charging at an appropriate time to centre load on 4am. For example, if a 4 hour charge is required, then start charging at 2am and finish at 6am. For charge durations longer than 6 hours, the charge would need to start early enough to avoid charging beyond 7am (7:30am absolute latest).

For charging during the day, it would be desirable for the EV vehicle user to be able to nominate the quantity of the top up required and by what time. This functionality in conjunction with a ripple receiver would ensure that an adequate day charge is received whilst still enabling some control capability by a network operator. The EV charger would only permit ripple interruption of the charge if sufficient time were available to get the required quantity of charge.

If two-way communication between the EV vehicle charger and the network company becomes economic in the future then smarter control regimes can be implemented.

There are a number of regimes that could be applied to EV charging and it is important that the complexity and cost of the regime is appropriate for the problem being resolved. The timing of various approaches such as smart chargers, ripple control, two way communications and smart meters with real time pricing will be dependent on the uptake of EV's and the pace at which smart network initiatives become economic in NZ. The disaggregated nature of the NZ electricity sector creates challenges (that must be addressed) to implementing coordinated demand side management and smart EV solutions.

7.2 Effects on Power System Reserve Requirements

A key driver of the GEM model used in this study for developing system expansion scenarios is the requirement to meet peak demand, with a reserve capacity margin. In addition to installing new plant to meet load, new plant may on occasions be required to ensure that this reserve constraint is satisfied. The reserves required to cover the failure of the largest plant on the system are specified year by year in the input data for the GEM model. The capacity constraint is a factor driving the construction of a considerable amount of peaking plant, often open cycle gas turbines, fuelled by either gas or diesel. This type of plant has a lower capital cost per MW of installed capacity than either the more efficient thermal plant intended for base load operation, or renewable sources such as wind or hydro. Hence these peakers are often the most cost effective means of providing capacity that will have low utilisation.

Interruptible load and demand side management are also used to reduce the amount of additional capacity required to meet peaks and to provide the required reserve margin. Electric vehicle charging is a load that can be interrupted and offers potential to reduce reserve capacity requirements. The following sections outline a variety of ways in which electric vehicles could contribute to improved power system operations[52].

7.2.1 Power System Reserves

The power system requires reserves of a number of types to maintain power system performance within the limits required and to ensure adequate reliability. Most of these reserves are currently provided by generation plant and are purchased by the System Operator. The cost of reserves is ultimately met by electricity consumers, and results in less efficient operation of some generation plant, increased CO_2 emissions, and additional capital investments. In general, the provision of reserves requires some partly loaded generators to be connected so that they can automatically provide additional generation when required. For example, if a generator trips out of service, additional replacement generation is needed within a few seconds to maintain generation and load balance.

Two main types of reserves are required - frequency keeping reserves which are constantly adjusting to take up moment by moment variations in load and contingency reserves. A larger quantity of contingency reserve is required, as this is utilised to replace generation lost when a unit trips out of service. The largest unit typically has a capacity of about 360 MW. See Appendix 2 for a discussion on system reserve requirements.

Electric vehicle chargers are particularly suitable for providing some of these services, freeing generation resources for other purposes or enabling plant to be operated more efficiently and in the long run reducing the requirements for the construction of new plant.

7.2.2 Dynamic Demand

Dynamic demand technology is intended to allow loads which are not time critical to play a role in power system load and generation balancing. These loads are fitted with a controller which reacts to changes in power system frequency. If wind generation, for example, were to drop suddenly, a reduction in frequency occurs throughout the power system, and loads fitted

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[52] Vehicle to Grid Power Transfer: some studies have considered the possibility of electric vehicle batteries being used to supply energy to the grid at peak times. Given suitable controls on chargers and with appropriate control by the system operator, this may be feasible. However, battery life is influenced by the number of charging cycles for most current technologies and vehicle to grid power transfers would reduce battery life. Consequently, vehicle to grid transfer is not seen as a likely option at present.

dynamic demand controllers can reduce their consumption for a short time while alternative generation ramps up. A study has been carried out for the UK Department of Energy and Climate Change into the potential for such loads to facilitate the operation of wind generation, facilitating the achievement of renewable energy targets.[53]

In the United States, the Pacific Northwest National Laboratory has developed its "Grid Friendly Controller"[54]. It responds to changes in system conditions in about a quarter of a second, and is intended to support the system over the 10 minutes required for thermal plants to ramp up to replace lost generation. This device costs about US$25 per appliance

7.2.3 Reserves Supplied by Electric Vehicle Chargers

Electric Vehicle chargers are ideal source sources of dynamic demand. Each charger is a relatively large load, and a reduction in charging rate for a few minutes is unlikely to be noticeable to consumers. The additional cost of installing these controls will be insignificant, based on the cost quoted for the Pacific Northwest Laboratories device.

For the 80% uptake scenario, the modelled off peak and shoulder period charging load is approximately 140 MW in 2025, and reaches 400 MW by 2033, as in figure 18. The latter exceeds the reserves assumed to be required in the GEM model simulation of power system development, indicating the considerable scope for this load type of load to supply reserves.

Contingency reserves are categorised as "instantaneous" or "sustained", depending on their response time. These reserves are not called upon frequently, and the duration of the reduced charging would be only a few minutes. Hence the overall effect on slow rate charging would be negligible. Given sufficient incentives, even high rate charging applications might participate in the provision of reserves of these types. Providing frequency-keeping reserves would seem to be more difficult, as it requires both increases and decreases in load. This service is used almost continuously, unlike the instantaneous and sustained reserves, which are called upon only infrequently. Large charging stations, associated with battery swapping, might be suitable for the more complex controls required. Communication with the system operator might also be needed to ensure that adequate adjustment capacity was available, which would be more practicable for larger charging installations.

The parameters of the control systems required are likely to require consultation with the system operator to ensure optimal system response. If dynamic demand was to largely replace reserves supplied by generators, some form of communication might be needed so that the System Operator can determine how much of this load is available to provide reserves. It would be necessary to estimate how much the load will be reduced when frequency falls, how quickly it will be reduced, and the rate at which the load will be restored to its nominal full output value. If too much load were to be reduced, it is possible that system frequency would rise too far, and exceed the nominal 50 Hz by too much, resulting in some controllers increasing loads, causing the system frequency to oscillate.   The inertia of loads, such as electric motors, influences system frequency response, so some complex analysis is required to obtain an optimal response. However, because the electric vehicle charger loads have no inertia, and would be controlled by modern electronic equipment, it would be possible to design controllers that could be set to behave in the required way.

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[53] "The Potential for Dynamic Demand", Department of Energy and Climate Change (UK), November 2008.
[54] "Grid Friendly Controller Helps Balance Energy Supply and Demand", Pacific Northwest National Laboratory, Richland, Washington, USA.

7.2.4 Voltage Response Characteristics

The response of loads to reductions in system voltage plays an important part in power system performance during fault situations. These faults consist of short circuits from transmission lines to the ground or between the lines of the three-phase transmission system. When these short circuits occur, the power system voltage drops over a wide area.

Different loads react in various ways to the reduction in voltage. Resistive loads, such as heaters and hot water cylinder elements, reduce their power consumption to an amount proportional to the square of the voltage. This is helpful behaviour, as that load is now drawing less current, which helps reduce the further fall in system voltage. Some loads draw a constant power, irrespective of voltage. Therefore these loads draw larger currents during reduced voltage situations, which increases the stress on the power system.

To assist in stabilising the power system under fault conditions, electric vehicle chargers could be designed to reduce the current drawn as voltage falls. As these situations are infrequent, and short lived, the effect on battery charging would be insignificant.

8 Carbon Dioxide Emissions

One of the primary drivers for utilising electric vehicles is the associated reduction in carbon dioxide emissions. This reduction primarily arises from the displacement of hydrocarbon automotive fuels which would otherwise have been consumed by ICE vehicles. The other significant impact is the resultant emissions from the generation of electricity to charge the electric vehicles. This impact varies from country to country, depending on the options for generating the additional energy required. For example, in a country where the incremental electricity is generated from coal, the large majority of the emissions savings from reduced automotive fuels use would be lost[55]. Should the incremental electricity be generated from lower emission sources, the net reduction in carbon dioxide emissions could be increased substantially. In New Zealand there is potential to reduce carbon dioxide emissions from the power system by displacing fossil fuelled plant with renewables.

8.1 Power System Emissions

The somewhat counter intuitive result shown in Table 8 that emissions can be reduced with an increasing load is achieved due to the flattening of the power system load curve. This changes the optimal mix of new plant construction, favouring the construction of renewable technologies in place of fossil fuel plants, as described in Section 6.7.2.

Note that as stated in section 6.6, the GEM planning model is a high level, long-term expansion-planning tool. A more detailed dispatch planning model is likely to give results which differ in respect of some of the finer details – the data given here shows approximate emissions trends only.

However, the differences are small and depend on the level of control over the electric vehicle load:

- For the 80% uptake case, a reduction in generation system emissions of 0.68% is achieved, if the charging times are controlled (Table 8).

- For uncontrolled charging, assuming that this occurs uniformly across all hours of the day, an increase in emissions of 433,000 tonnes or 0.32% occurs over the period 2010 to 2039.

Scenario	Lower	60%	80%	Upper
Reduction in CO_2, millions of tonnes	2.48	1.59	0.91	0.81
% of total electricity system emissions	1.85	1.19	0.68	0.60

Table 8: Reduction in Power System CO_2 emissions over the period 2010 to 2039 with electric vehicle charging (85% off peak and shoulder, no charging during super peak hours)

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[55] China Charges Up: The Electric Vehicle Opportunity, McKinsey and Company, October 2008.

8.2 Vehicle Tailpipe Carbon Dioxide Reductions

Any reduction in vehicle tailpipe carbon dioxide emissions arising from the adoption of electric vehicles will depend on the perceived future composition of the national vehicle fleet if they fail to materialise as a viable option and, if they are viable option, the type and operation of the vehicles they displace. Carbon dioxide emissions from vehicles are directly related to the quantity of hydrocarbon fuel consumed (at present virtually all petrol and diesel) which in turn is related to a diverse range of factors, including vehicle size, condition and age; fuel type; distances travelled; and driving and traffic conditions.

To determine the reduction in carbon dioxide emissions in each of the electric vehicle scenarios, a number of assumptions have been made to account for these uncertainties:

- Only HEV, petrol and diesel vehicles will be displaced by electric vehicles during the study period. Alternative fuels such as biofuels or hydrogen will be utilized to an insignificant extent or will not be displaced by electric vehicles.

- There is some debate as to the extent to which HEVs will displace conventional petrol and diesel vehicles in the future. HEVs have a significantly lower fuel consumption[56] than their conventional petrol counterparts and the future uptake of these vehicles will affect total fleet tailpipe emissions. Two base cases without electric vehicle uptake have been assumed:

    o Low HEV: the uptake of petrol, diesel and HEVs is in the same relative proportions of these vehicles in the Lower Case electric vehicle scenario.

    o High HEV: HEVs only take up the share of electric vehicles in the Lower Case electric vehicle scenario.

- Each electric vehicle displaces either a diesel or petrol vehicle operating the same annual distance or, for the purposes of this study, 12,235 km per vehicle per annum.

- Fuel consumption of petrol vehicles is based on an average of 10.7 litres/100 km for all light passenger and commercial vehicles in 2007[57]. Fuel consumption is assumed to reduce by 1.35% annually[58] for new vehicles due to improvements in internal combustion technology, starting at 9.5 litres/100 km for new vehicles in 2008.

- Average diesel fuel consumption is 74%[59] of the petrol counterpart or 7.0 litres/100 km in 2008 and will decline by 1.15% annually due to technology improvements. This is probably a conservative estimate, implying that electric vehicles will tend to replace smaller diesel vehicles.

The resultant reductions in carbon dioxide tailpipe emissions are shown in Figure 26, increasing with the population of the electric vehicles but being offset somewhat by the improving fuel consumption of petrol and diesel vehicles. The scale of reductions range from over 3 million tonnes of CO_2 per annum in 2040 for the Upper and 80% Uptake Scenarios to 1.5 million tonnes for the Lower Case Scenario. These are diminished by about 0.5 million tonnes if the High HEV base case is assumed due to the lower fuel consumption of HEVs compared to conventional petrol vehicles.

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[56] It is assumed that HEVs have 53% of the fuel consumption of conventional petrol vehicles. Based on the relative performance of the Toyota Prius and Camry 2.4 litre saloon as listed in the US DoE/EPA's Fuel Economy Guide, 2009.
[57] Derived from Transport Monitoring Indicator Framework, MoT, 2009.
[58] Hyder *op cit*, after UK Department of Transport.
[59] Based on the relative fuel consumption of equivalent petrol and diesel BMW, VW and Mercedes Benz models. US DoE/EPA's Fuel Economy Guide, 2009.
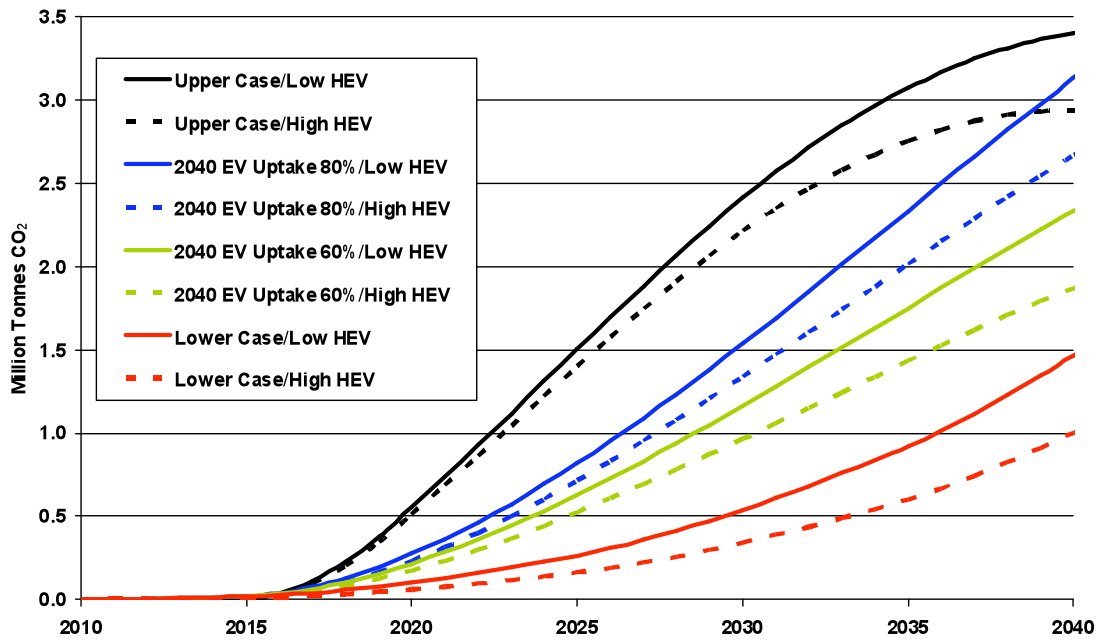
Figure 26: Reduction in Tailpipe CO$_2$ Emissions

The reductions in carbon dioxide emissions anticipated from the tailpipes of the displaced of petrol and diesel vehicles are significantly higher than the reductions anticipated to occur simultaneously in the power generation system.

Scenario	Lower	60%	80%	Upper
Power System	2.48	1.59	0.91	0.81
Tailpipe Emissions				
Low HEV Case	11.94	23.36	30.90	44.47
High HEV Case	7.73	19.14	26.68	40.26

Table 9: Reduction in CO$_2$ emissions 2010 to 2039 (total million tonnes)

Appendix 1: GEM Model Details

The objective of the GEM model is to determine a least cost generation system expansion plan. Electricity demand is an input to the model, along with details of the existing generation system and a list of possible new plants. GEM finds the least cost expansion path by selecting the plants to be built and their commissioning dates. It does not consider the possibility of generation companies exercising market power to increase their profits – an efficient market is inherently assumed. This assumption is commonly made when carrying out long-term generation planning studies. It is equivalent to assuming that in the long term all profitable new generation construction opportunities will eventually be exploited.

A mathematical optimisation problem is solved by GEM, using a commercial mixed integer linear solver. The key input data includes:

- forecast electricity demand per island, on a quarterly basis, in load duration curve format
- existing generation plant parameters
- potential new build details, including capital and other fixed costs
- earliest commissioning dates for new plant
- retirement dates for existing plant
- fuel costs, year by year
- Shortfall costs
- Fuel availability
- Hydro generation patterns
- HVDC link capacity

When calculating the least cost expansion plan, the following costs are included:

- thermal plant fuel
- supply shortfall penalties
- new generation plant capital
- fixed operation and maintenance
- variable operation and maintenance
- carbon charges

When determining the commissioning dates for new plant and retirement dates for existing plants, a variety of constraints are enforced to achieve a realistic system expansion plan. A key constraint is the load balance equation - that total generation plus shortfall equals total load. As shortfall is assigned a higher cost than any generation, it will only occur when there is inadequate generation capacity. This can be due to constraints on the available fuel quantities or low inflows to hydro plants, as well as by insufficient total installed generation capacity on the system.

An additional constraint enforced is that installed capacity must exceed peak demand when both the largest generation unit is out of service and a part of the HVDC link capacity is not available.

High voltage transmission system constraints are not modelled explicitly, except for the HVDC link. The planned HVDC link upgrades are included – south to north capacity increases to 1000 MW in 2012 and to 1200 MW in 2014.

Load forecasts used are for grid exit point (GXP) loads, so distribution system losses are included implicitly. An adjustment is made to the load forecasts to account for AC transmission system losses, so that the correct generation requirement is seen by the GEM model.

Because the model is required to select a date for the commissioning of a variety of discrete generation units or generation plants, it is attempting to solve an integer problem. Problems of this type involve the solution of a large number of sub problems. While a process of trial and error is used, the search is guided by a variety of strategies that have been found to be useful. The integer search can be a very time consuming process, but the mixed integer solvers used are able to carry out the process with no user intervention. Only a relatively small number of control parameters need to be selected by the user to obtain good solver performance. Due to the difficulty of solving these mixed integer problems, the true optimal solution is generally not found – just a result that is likely to be very close. Consequently, small changes to the input data can result in some changes to results which are essentially random, but which have only a small effect on the overall cost of system development.

Further information is available from the web site gemmodel.pbworks.com

Appendix 2: Power System Reserves Requirements

The power system requires reserves of a number of types to maintain system performance within the limits required and to ensure adequate reliability. Reserves are called upon to compensate for the continuously varying nature of total system load – generation must also vary to maintain balance between supply and demand. Other reserves are required to deal with contingencies – the sudden, unexpected failure of a major generation unit, or of one pole of the HVDC link. If these reserves were not provided, load shedding would be needed when a major plant failure occurred.

Most of these reserves are currently provided by generation plant and are purchased by the System Operator (a service provided by Transpower). Electric vehicle chargers could provide some of these services, freeing generation resources for other purposes or enabling plant to be operated more efficiently and in the long run reducing the requirements for the construction of new plant.

Three types of reserves will be considered – frequency keeping, instantaneous and sustained.

Frequency keeping reserves are required to maintain system frequency at 50 Hz due to the continual deviations in frequency caused by changes in total system load. The effect of an increase in load will be considered in the following discussion. This load change occurs without warning and is due to the aggregate actions of all consumers. While a single large industrial load increase can create a measurable effect, some changes are simply random, and others are part of a trend of increasing load, for example as lighting load increases at dusk. Total load now exceeds total input energy to the power system from all generators - the power produced by the various hydro and steam turbines etc is unchanged. The required additional electrical energy is supplied by generators giving up rotational energy, i.e. by spinning more slowly. Almost all generators are of the synchronous type, meaning they rotate at a speed determined by the system frequency and the number of poles fitted to the generator. All these synchronous generator begin to slow down. A lower generator speed of rotation results in a lower system frequency.

Most generators connected to the system are fitted with a speed governor. The effect of these governors is that generator output is inversely proportional to their speed – the governor is a proportional error control device. These changes in output occur about a set point, or nominal output, which is selected by the machine operator. A reduction in system frequency and generator speed of rotation is detected by every generator governor, causing them to increase their generator's output, unless the machine is already at full load. Because these governors are proportional error controllers, they cannot restore system frequency to the required 50 Hz – there must be some deviation from 50 Hz for the generator governor to have changed output from the set point or nominal output that the machine operator has requested. The role of the frequency keeping plant is to continue increasing output until frequency is restored to 50Hz, at which time all other generators are likely to be once again operating at their nominal output or set point.

The frequency keeping plant is required to be able to increase and decrease output by specified amounts. As its output approaches these limits, a system wide redispatch will be carried out by the System Operator resulting in changes to the set points of the marginal generators and perhaps other generators as well. (The marginal generator is the most expensive plant connected to the system, and so will not be fully loaded.)

Instantaneous reserve can be provided by generating plant that is synchronised to the system, but which is not operating at full load. The purpose of this plant is to provide additional generation in the event of a contingency occurring, i.e. in the event of some other generator tripping off the system. Such an event can result in a sudden and relatively large imbalance between generation and load (depending on the size of the unit), and consequently a rapid fall

in system frequency. Instantaneous reserves are specified to be those that can react automatically within 6 seconds. After this length of time, the system frequency is required to have reached its minimum level, and begun to climb back towards 50 Hz. The response required is too rapid for manual intervention, and so is handled by generator governor action. Instantaneous reserves are offered into the electricity market by generation companies, and are cleared simultaneously with energy offers. Capacity that is providing energy can not also provide reserves. The simultaneous market clearing process allows an optimal trade off to be made for each generator as to whether it should provide energy or reserves.

The response characteristics of individual generators are determined by the physical arrangement of each unit, in addition to the governor design. For a hydro turbine, an increase in output requires a greater flow of water. The unit's penstock is full of water moving at a constant speed prior to the contingency. To increase power output, the governor opens the wicket gates located within the turbine housing (scroll case). This results in changes in pressure in the penstock, and causes the water in the penstock to accelerate. The maximum rate at which turbine power output can increase is limited by the rate at which water in the penstock can accelerate. Turbines with long penstocks, and correspondingly large volumes of water to accelerate, can generally increase output more slowly than those with short penstocks.

For thermal plants, rates of change in output are governed by boiler steam supply arrangements, thermal issues within turbines, etc.

Sustained Reserves are those provided on a longer time scale than the instantaneous reserves. While the function of the instantaneous reserves is largely to arrest the fall in system frequency, the role of sustained reserves is to bring the system frequency back into its required operating range. These reserves are often measured as the increase in output 60 seconds after the occurrence of a contingency. For example, a hydro generator with long penstocks might be able to provide a small amount of additional power after 6 seconds, but a much larger amount after 60 seconds.