

**The impact of electrified transport on local grid infrastructure: a comparison
between electric cars and light rail**

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Abstract

This study examines the impact on the local electricity grid should electric vehicles (EVs) or a light rail transit (LRT) system be introduced to the city of Christchurch, New Zealand. Spatial analysis highlighted that EV owners would not be evenly distributed throughout the city, and the initial stages of a proposed LRT network would cover only a limited area. Therefore, a few local power substations would have to provide the

majority of additional power for both electric transport modes. Without management of EV charging patterns, one of the local substations would be overloaded if more than 2.6% of the Christchurch light vehicle fleet were EVs. The power demand from a LRT system would not overload the local grid given current demand levels. However several substations would need an upgrade 4 years earlier than current plans.

A comparative analysis shows that despite the power demand from an EV fleet being higher than the demand from a LRT system (on a equal passenger kilometre per day basis), demand side management methods would allow shifting EV charging off peak time whereas a LRT system would still contribute significantly more to peak load.

Key words: Electric vehicles, light rail transit, peak demand

1. Introduction

Given the uncertain future of fossil fuel availability, climate change and associated regulations on CO₂ emissions, new technologies that reduce the current dependence on fossil fuels are appearing on the market. Such technologies include increased renewable electricity generation as well as new transport systems. A potential way to reduce fossil fuel dependence in the transport sector is to shift towards electrified transport modes. These transport modes include public transport (electric light/heavy rail, trolley and electric buses) and private electric vehicles. This shift is all the more beneficial in a region where the majority of electricity generation is from non fossil fuel resources.

National and local governments have been promoting both EVs and public electric transport. For example, in Paris and London, EV charging infrastructure and incentive

programs have been announced (The Canadian Press, 2011; Mayor Of London, 2009). In New Zealand, the city of Wellington operates an electric rail network, and the city of Auckland is undertaking a rail electrification program (Joyce, 2009). In addition, electric vehicles have been promoted by electricity retailers/generators such as Meridian Energy using the Mitsubishi iMiEV cars (Shaw, 2009). In 2010, 74.2% of NZ electricity generation came from renewable sources, (predominantly hydro), and new generation is projected to come largely from renewables (MED, 2011a, MED 2011b). This puts New Zealand in a good position to reduce its dependence on fossil fuels for transport by switching to electrified modes, provided risks from daily/seasonal variability can be managed, particularly given potential climate change effects on hydro and wind electricity generation (Renwick et al. 2010).

Increasing the amount of electric transport will require not only more electricity to be generated, but also consideration of where and when power is required. Indeed, electricity generation, transmission and distribution infrastructure are under increased pressure during peak times, when demand is significantly higher compared to the daily average load. For New Zealand, peak demand occurs during the winter months between 6pm to 8pm. Electricity providers are required to deal with increasing peak power demand and adapt their infrastructure accordingly. The growing demand may not occur evenly across an area; therefore the geographic distribution of demand must be estimated to identify specific local infrastructure upgrades required. When examining the potential impacts of electrified transport, consideration should therefore be given to the local grid infrastructure as well as to the total energy and regional power demand.

2. Goal and overview of paper

This research provides a geographic and time based power load profile for an electric vehicle (EV) fleet and a light rail transit (LRT) system. By identifying where and when increased power demand will occur, local power distribution providers can identify which areas will require infrastructure upgrades and when they may be needed. Should widespread electric transport be the chosen alternative, such information would help local authorities anticipate potential additional costs due to growing demand.

The following section of this paper reviews previous studies in which the impact of electric transport on the grid has been examined. Section 4 of this paper explains the overall method, in which the case study of Christchurch is described and the procedure in which the impacts on the grid are evaluated and compared. Sections 5 and 6 provide the power demand estimation for the EV fleet and LRT system respectively, as well as the identification of the impacted local power infrastructure. The impacts from both are compared within Section 7. The implications on policy making are discussed in Section 8 with section 9 providing final conclusions.

3. Review of electric transport studies and their impacts on the grid

A significant amount of research worldwide has been done on EV energy and power demand on a national and regional scale. These studies are country specific. For example, in New Zealand, Duke et al. (2008) estimated that a 2 million EV fleet would require an additional 1350MW of wind generation, providing an additional 4900 GWh per year. This would be a significant increase on the total installed capacity of 9,667MW in New Zealand, which in 2010, generated 43,401 GWh (MED, 2011). In

Ontario, Hajimiragha et al. (2010) analysed the feasibility of utilising grid off-peak potential for charging plug-in hybrid electric vehicles (PHEVs). They concluded that 6% of the total vehicles in Ontario and 12.5% in Toronto could be PHEVs without any additional transmission or power generation investments beyond those currently planned. Hajimiragha et al (2010) identified the need to study technical problems such as overloading distribution feeders in more details.

Some studies have examined the impact of EVs on a more local level by focusing on distribution issues. In New Zealand, Duncan et al. (2010) undertook an analysis based on a distribution network infrastructure model to analyse how EV charging could affect power quality. Their analysis revealed that 15% of the NZ national fleet could be EVs without a need for an infrastructure upgrade. A similar study by Lambert (2000) has been conducted in California by collecting data from residential appliances and EV chargers. The study concluded that power quality (total harmonic distortion) should not be a cause for concern. The main cause for concern is the overloading of the distribution transformer with widespread use of EV chargers. The study recommend planning services to consider real current load value (kVA) and power factor to base their analysis (Lambert, 2000). In Europe, Perujo et al. (2010) estimates both the impacts of EV uptake on the Milan (Italy) area electric grid in term of power demand based on market penetration studies. Perujo et al. (2010) concluded that without appropriate regulation on vehicle to grid behaviour, EV could heavily impact the daily electric power demand, especially in a high uptake scenario where more than 20% of light vehicles are EVs. A study by Mullan et al. (2011) has been undertaken to assess regional power supply and transmission in Western Australia. The authors concluded

that even without controlling charging times, a 200,000 EV fleet (10% of the current local fleet) could be charged on the local grid before there is any significant impact on local peak demand. They also suggest that EVs would be clustered, and how it would be more difficult to predict where they will be charged during the day as oppose to the night time where the home would be the obvious location for private EVs.

The issue of non-even distribution of EVs and the resulting impact on the local distribution network has been identified by a number of studies. Shirmer et al. (1996) undertook a predictive analysis of EV distribution in Southern California using GIS (Geographic Information System). They noted that the use of even one single charger could potentially double a household electrical demand. Furthermore they concluded that although generation and transmission infrastructure could sustain an increasing demand from EV charging, it is likely that EV owners will be spatially clustered, creating a disproportionate load on some local power substations. This issue has also been examined by Mohseni and Stevie (2009) for several North American cities considering the need for new electric capacity, the timing of that capacity need, and the potential spatial clustering of EVs using a statistical procedure. They concluded that the main risk in EV uptake lies with the utilities' abilities to successfully manage local distribution issues, time of use pricing, charging venues, and infrastructure management. It was also shown that the up-take of EVs in the near term was unlikely to pose risks to utilities, but infrastructure additions should not be ignored for too long when a robust EV market eventuates.

With respect to time of use, Rahman (1993) showed that off peak generation must be looked at as well as distribution capacity. EV charging could induce a new peak in electricity demand and jeopardize the load management program currently in use. Denholm and Short (2006) in the U.S., looked at the benefits from optimally dispatched EV charging to ensure EVs are charging when the electricity price is at the lowest. They conclude that up to 50% of EV penetration with optimal dispatch would increase the per capita electricity demand by around 5-10%, depending on the region evaluated but would require no new electric generation capacity.

The electricity demand profile from an EV fleet is different from an electric LRT system in a number of ways. The energy demands for a LRT system are lower per passenger km travelled. Newman and Kenworthy (1999) report the average energy per passenger kilometre of rail travel for cities in Europe (electrified rail) to be 0.49 MJ/pkt (140 kWh/pkt). For the same cities, the (liquid fuelled) energy required for car travel is 2.62 MJ/pkt (727 Wh/pkt). Although an electric vehicle requires less energy than a traditionally fuelled vehicle (as shown in section 5), an electric rail (or LRT) system requires the least energy per passenger kilometre travelled. When considering the effect on the electricity grid, the fact that a LRT system requires power during morning and evening peak times makes the impact potentially larger than an EV fleet. Much of the research on LTR is currently focused on reducing energy and power demand using regenerative braking and onboard batteries/supercapacitors. The effects of energy storage systems for light rail transit (LRT) systems have been analysed by Yu et al. (2010). The authors showed that battery storage combined with regenerative braking can improve energy saving performance. Moscovitz et al. (2010a) looked at LRT

Citadis line T3 in Paris to evaluate impact of supercapacitors on energy saving. They concluded that supercapacitors, which have a very high power density, enable a quick recharge and allow energy management optimization and autonomy from the overhead lines. Steiner & Scholten (2006) and Steiner et al. (2008) outlined potential energy saving capacity using supercapacitors of approximately 30%. These studies highlight potential reduction of the impact on the grid by using embedded energy storage. Regenerative braking allows a reduction of overall energy demand and the power density of supercapacitors allows for reduced peak power demand from the light rail system and thus a reduced pressure on the grid. Albrech (2004) looked at the possibilities of train running time modification in order to reduce power peaks and energy consumption (through optimised use of onboard batteries) using an optimization algorithm (genetic algorithm). Applied to a German DC electric rapid rail system, it was shown that train time modification led to significantly reduced energy consumption and peak power.

There is a need to plan for new energy and power demands from electric transport at a broad level. Efforts are being put into reducing energy and power consumption from LRT systems. Also, a number of researchers have highlighted the need to understand the new power demands on a finer level; specifically, the actual location of EVs and the added load to local distribution infrastructure. The power demand from each transport mode must be estimated to ensure the existing distribution network can cope with the new demand. The spatial distribution of EVs needs to be estimated in order to predict where the additional load must be planned for. The same way, the LRT system location should be analysed to identify the local power substations which

would provide for the additional power. In addition, electric trains and private vehicles have been compared in term of energy needs but not in terms of power demand and the impact on a local grid.

4. Method

This research is based on the city of Christchurch, New Zealand. It is the second largest city in New Zealand with a population of approximately 377,000 (Statistics NZ, 2011). As of 2010, Christchurch has no public electric transport service, with the exception of a small historic tram loop in the inner city serving predominantly tourists. Electric cars requiring battery charging from the national grid are not available on the New Zealand consumer market. Another factor for selecting Christchurch as the case study city is that a light rail system has recently been proposed as part of the Christchurch City Council recovery plan; established after the city was hit by a series of major earthquakes in 2011 (Christchurch City Council, 2011).

The impact of EVs and LRT will be evaluated using the historic load demand pattern of 2010. The additional power demand from both an EV fleet and LRT system will be calculated based on existing technology and information on New Zealand travel patterns. The distribution of the EV fleet and the location of the LRT line are also estimated in order to evaluate the local impact on the grid and identify which local power distribution infrastructure would be impacted.

The impact of each transport mode on the local grid will be compared based on the same daily passenger kilometres travelled.

5. EV geographical distribution and load

As highlighted by Shirmer et al. (1996), EV spatial distribution is likely to be uneven, resulting in an uneven impact on the local distribution network. EVs have a limited range and are generally smaller and more expensive than the average car in Christchurch. Therefore, during the initial uptake of EVs, they are unlikely to have uniform appeal throughout the city and will likely be clustered in certain areas.

Since 1998, the Toyota Prius Hybrid car has been widely available and can be considered the first step towards plug-in electric vehicles. Indeed, in the U.S., some Prius dealerships have started converting hybrid Prius cars into plug-in electric vehicles (Goldenberg, 2009) and Plug-in-Hybrid Electric Vehicles (PHEV) are appearing on the market. Furthermore, EV manufacturers believe that the current Prius owners are more likely to switch to full electric vehicles (Chambers, 2010). As Prius owners appear more likely to buy an electric vehicle or convert their vehicle to plug-in, the location of current Prius owners in Christchurch is used in this study as an indicator of future EV owners' location, and hence where night time charging would occur. However it should be noted that this is an assumption, and true location of EV uptake will depend on the target market, and perceived differences between pure EVs and hybrids.

Figure 1 shows a map of Christchurch with the approximate location of Prius vehicle owners in 2009. It can be seen that there is a higher density of Prius vehicles in the western suburbs, especially in the residential areas supplied by Fendalton, Ilam and McFaddens local power substations. This result is in accordance with the studies described in Section 3 which concluded EV ownership is likely to be clustered spatially in a local area.

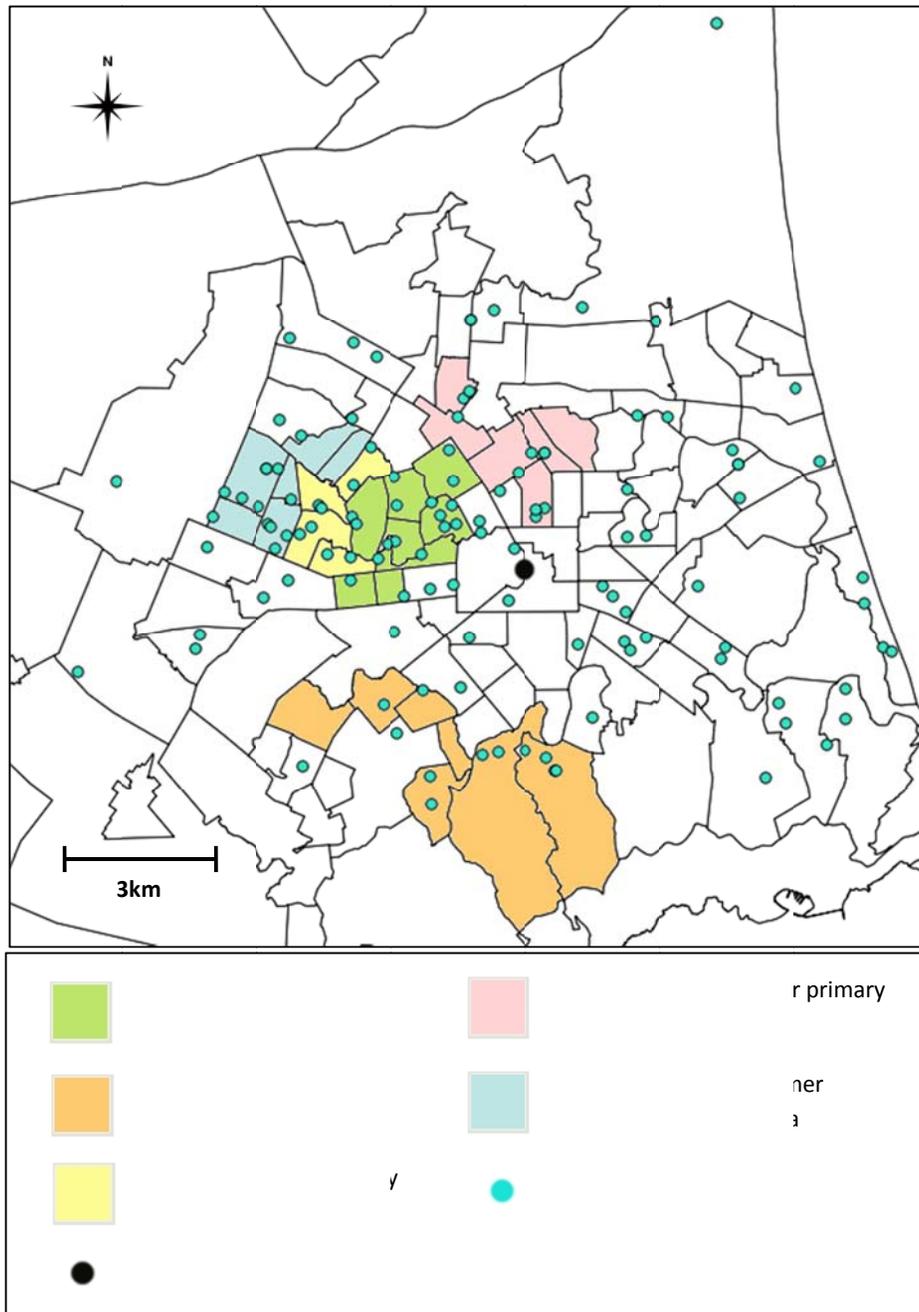


Figure 1: Geographic location of Toyota Prius and transformers catchment areas with the highest number of hybrid vehicle in Christchurch.

The results were obtained from a Warrant of Fitness (WOF: compulsory regular check to ensure light vehicle is safe to drive on the road) dataset provided by New Zealand Transport Agency (NZTA). This dataset provides data on every NZ light vehicle for each

WOF inspection during the last ten years and gives information such as vehicle age, mileage, make, model and owner address. Data for all privately owned Toyota Prius in Christchurch was extracted and the owner addresses have been processed to create the spatial distribution shown in Figure 1. This study only considers private cars (non-company cars) that will be charged from a residential connection. The data processing identified 122 privately owned Toyota Prius in Christchurch which represent a small fraction of Christchurch private light vehicle fleet (0.08%).

Each EV introduced to Christchurch will require power from the local distribution network. Table 1 outlines the five Christchurch electricity distribution substations (out of 30 in Christchurch City) with the highest number of Prius in their supply catchment area. Given a total number of EVs introduced to Christchurch (discussed in Section 7), the proportions shown in Table 1 are used to estimate the number of EVs being supplied from each substation. Each local substation supplies several area units in different proportions, specified by the local distribution manager. These proportions have been used to calculate the ratio of Prius in each catchment area.

Table 1: Substations with the highest number of Prius in their supply “catchment area”

Zone Substations (or transformers)	proportion of Prius within substation catchment area
Fendalton	11.9%
Hawthornden	10.5%
McFaddens	7.9%
Hoon Hay	7.2%
Ilam	6.2%

The amount of power and the time for charging after daily use must be estimated to predict the potential impact on the distribution network. Table 2 shows the energy and travel distance characteristics for 6 EV models (including two PHEVs and 4 all electric vehicles: BEV) that have been tested on road and could match New Zealanders' needs in term of commuting.

Table 2: Specifications, test data and km travelled per kWh on several EV models

Vehicle model	Type	Battery Capacity (KWh)	Electric range (theory)	Electric range (practice)	Economy kWh/km (Practice)	References and notes
Toyota Prius 2012	PHEV	5.2	24 km	19 km	0.274	Manufacturer specifications and test results from Cunningham (2011)
Chevrolet Volt	PHEV	16	65 km	54 km	0.296	Manufacturer specifications from Bartoli (2009) and test results from Edmunds (2010)
Nissan Leaf	BEV	24	160 km	127 km	0.189	Specification and test data from Nissan Leaf (2010a)
Mini-E	BEV	35	240 km	154 km	0.227	Manufacturer specification from Minispace (2011) tests data from Damasiewicz (2010)
Smart-EV II	BEV	16.5	135 km	116 km	0.142	Specifications and test data from Conway (2011).
Mitsubishi MiEV	BEV	16	125 km	95 km	0.168	Specifications and test data from MacDonald (2010).

The energy requirements of an EV depend on numerous factors such as weather conditions, driver style, use of air conditioning and other onboard devices. This

explains the significant difference between manufacturer specifications using ideal conditions (Nissan Leaf, 2010a), and vehicle test results also listed in Table 2. Plug-in-hybrid Electric Vehicle economy is lower than the average BEV. The mean efficiency ratio for a PHEV is 0.285 kWh/km whereas for a BEV it is 0.182 kWh/km. Therefore, the energy demand for EV charging will vary according to the BEV/PHEV ratio in the EV fleet in Christchurch. Table 3 summarises all variables used to calculate the power and time required to charge an EV after an average days travel in Christchurch.

Table3: EV power and energy parameter used to estimate power demand

Symbol	Variables	Value	Notes and Reference
$D_{\text{commuting}}$	VKT per day	21.6 km	Mean daily commuting distance in main NZ urban areas (Ministry of Transport, 2011)
E_{EV}	EV economy	BEV:0.182 kWh/km PHEV: 0.285 kWh/km	Mean values from EV test range data
N/A	Energy used per day	BEV: 3.93 kWh PHEV: 6.16 kWh	Using efficiency establish from EV test range data and mean travelled distance
T_{charging}	Time for charging after daily use	BEV: 1h40 PHEV: 2h30	According to (1)
E_{charging}	Charging efficiency	90%	Shoyen (2009)
$L_{\text{Distribution}}$	Distribution losses	4.84%	Orion (2010)
P_{Charging}	Charger output	3 kW	Charging level possible in NZ households
N/A	Charger input from residential socket	3.4 kW (230V/15A)	NZ households wiring specifications

A model of load demand due to EV battery charging developed by Qian & Zhou (2011) shows that the battery input power is dependent on the state of charge (SOC). As this study is focussed on the maximum power demand and duration of charge, a simple On/Off charging pattern has been approximated.

In New Zealand, residential connections are supplied at 230V/15A. Therefore a 3kW charging device could be used within EV owners' households without any electrical wiring upgrade. The charging process has an efficiency of 90%, therefore the average charging time for a Christchurch EV owner is two hours and fifteen minutes according to equation (1). The power demand from the EV charger will be the same during the charging time. Only the charging time will vary depending on the commuting distance and the type of EV (BEV or PHEV).

$$T_{\text{charging}} = \frac{D_{\text{commuting}} \times E_{EV}}{P_{\text{charger}} \times E_{\text{charging}}} \quad (1)$$

The New Zealand household travel survey indicates that 90% of cars are parked in a residential property overnight, with more than 80% parked between 6pm and 7am (Ministry of Transport, 2009). Without any control on charging behaviour, it can be assumed that most EV users would recharge their car from 6pm onwards. In this case, the majority of EVs would be on charge during electricity peak demand time (around 7pm).

Each local distribution transformer would supply a proportion of EV charging. The additional power demand from the EV fleet on each substation if all EVs are charging simultaneously is given in Equation 2:

$$P_{substation} = \frac{N_{EV} \times (1 + L_{Distribution}) \times P_{Charging}}{E_{Charging}} \quad (2)$$

Where:

- $P_{substation}$: The overall power demand from EV charging on a specific substation (in kW)
- N_{EV} : Number of EVs charging in a substation supply zone

The number of EVs in a particular catchment zone is calculated using the proportion listed in Table 1 and the total number of EVs assumed to be in Christchurch. The estimated number of EVs introduced in Christchurch is not based on a forecast; instead it will be set to match the number of passenger kilometres provided by the LRT system analysed in Section 6. This enables a comparison between both transport modes, which is provided in Section 7.

6. Light rail geographic distribution and load

Christchurch City Council (CCC) released a proposed plan for the Christchurch rebuild in August 2011, which briefly describes a potential LRT network. The first LRT line is intended to go from the international airport to the central city and would be approximately 15 km long (Sachdeva, 2011). For the purpose of this study, a LRT line going from the airport, through the centre of the city and finishing at the main sports stadium has been assumed (see Figure 2). This has been based on available information from the CCC and other factors such as density of population, locations of amenities and commuting patterns.

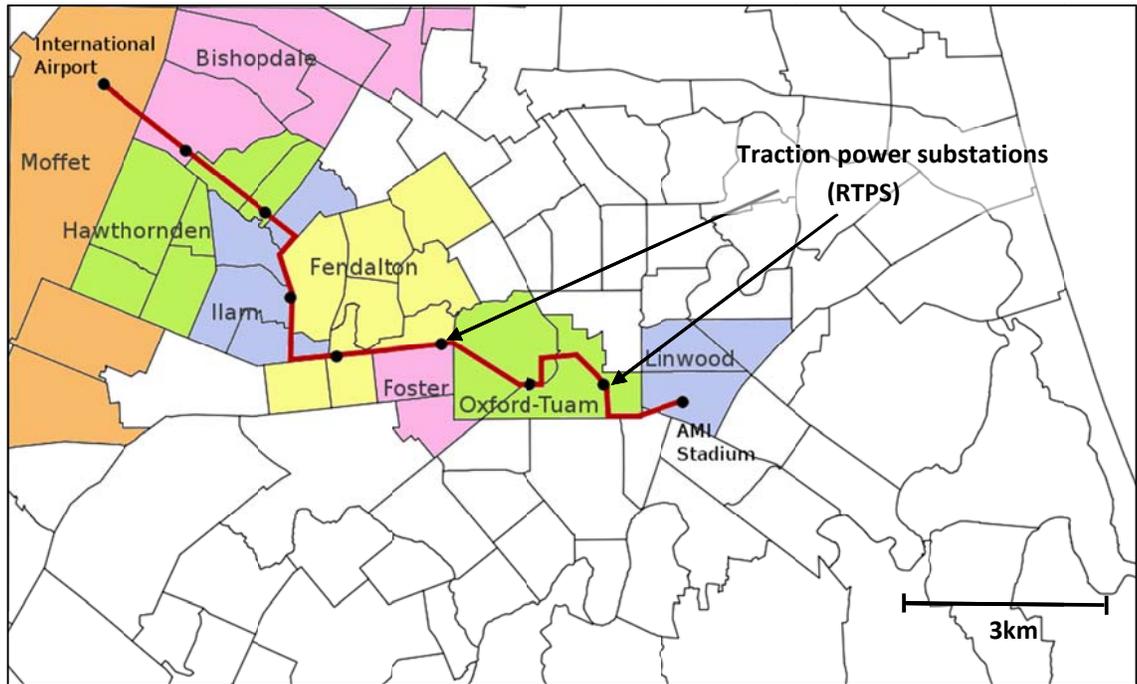


Figure 2: Light rail line with electric supply points and Orion distribution substation catchment zones.

A LRT line is supplied by several rail traction power substations (RTPS) located along the rail within a short distance from each other to avoid significant energy losses. The choice of distance depends on several factors, including the RTPS capacity, the timing between trains and the types of train used. For example, the Portland LRT system uses a space of 1.6 km between adjacent 1MW RTPS, with this distance being recommended for other LRT networks (Topalovic et al., 2009). For the purpose of this study a 1.6km space between adjacent RTPS is chosen. These are shown in Figure 2 and the distribution substation catchment areas are highlighted to identify which transformer will provide for each RTPS.

In order to model the LRT pattern, and hence determine the power demand, a similar city (in terms of population and spatial extent) which has a light rail network has been

selected; Orléans, France. The population of Orléans urban area is approximately 369,000, which is similar to Christchurch city population (377,000 inhabitants). In August 2011, an 18 km LRT line provided public transport across the central area of Orléans, with stops every 700-800 meters. The online timetable (TAO, 2011) showed a frequency of one train every 9 minutes during peak hours (from 7am to 7pm) with a travel time of between 2 and 3 minutes between adjacent stations. The maximum number of trains in service on the line at any one time is 12.

Given the similar city population size and LRT line length (18 km and 15 km) the parameters shown in Table 4 are used to model the Christchurch LRT system. In order to define the power demand from a single train, a number of train parameters need to be defined and these are provided in Table 5.

Table 4: Christchurch LRT line model characteristics

Parameter	Value
Operating hours	5am till 12am
Peak time	7am to 7pm
Frequency of train at peak time	Every 9 min
Average travel time between stops	2min30sec
Number of trains operating at peak times	10
Number of trains operating at off peak times	2 to 8
Mean time stopped in each station	20 seconds ^a

^a Based on an estimation from Moscovitz (2010b)

Table 5: Relevant power specifications for a 30m Citadis train from Alstom (model used in Orléans)

Symbols	Variables	Values	Notes and references
N/A	Vehicle length	30 m	Alstom Citadis specifications (Citadis, 2011)
N/A	Passenger capacity	200 (56 seated and 144 standing)	Alstom Citadis specifications (Citadis, 2011)
N/A	Maximum speed	70 km/h	Alstom Citadis specifications (Citadis, 2011)
N/A	Mean consumption	4-5k Wh/km	Moscowitz, 2010b
P_{mean}	Mean Power	200 kW	Moscowitz, 2010b
$P_{\text{Accelerati ng}}$	Maximum peak consumption (acceleration phase)	900 kW	Moscowitz, 2010b
P_{Stop}	Power for auxiliaries and comfort: air conditioning and light	50 kW	Moscowitz, 2010b
P_{Regen}	Max power from regenerative braking system	200 kW (NiMH batteries)	Coquery et al., 2004
L	Losses from local power utility to the pantograph	30%	Groeman, 2000

The power demand from LRT units depends mainly on the acceleration value (Coquery et al., 2004). Figure 3 provides a simple model for a LRT speed and power pattern between two consecutive stops. The train's speed is assumed constant once maximum allowed speed is reached until it approaches the next stop. A battery/supercapacitor pack allows energy to be stored from regenerative braking, and provides an output of 200 kW during the short acceleration phase to reduce maximum power demand from each train.

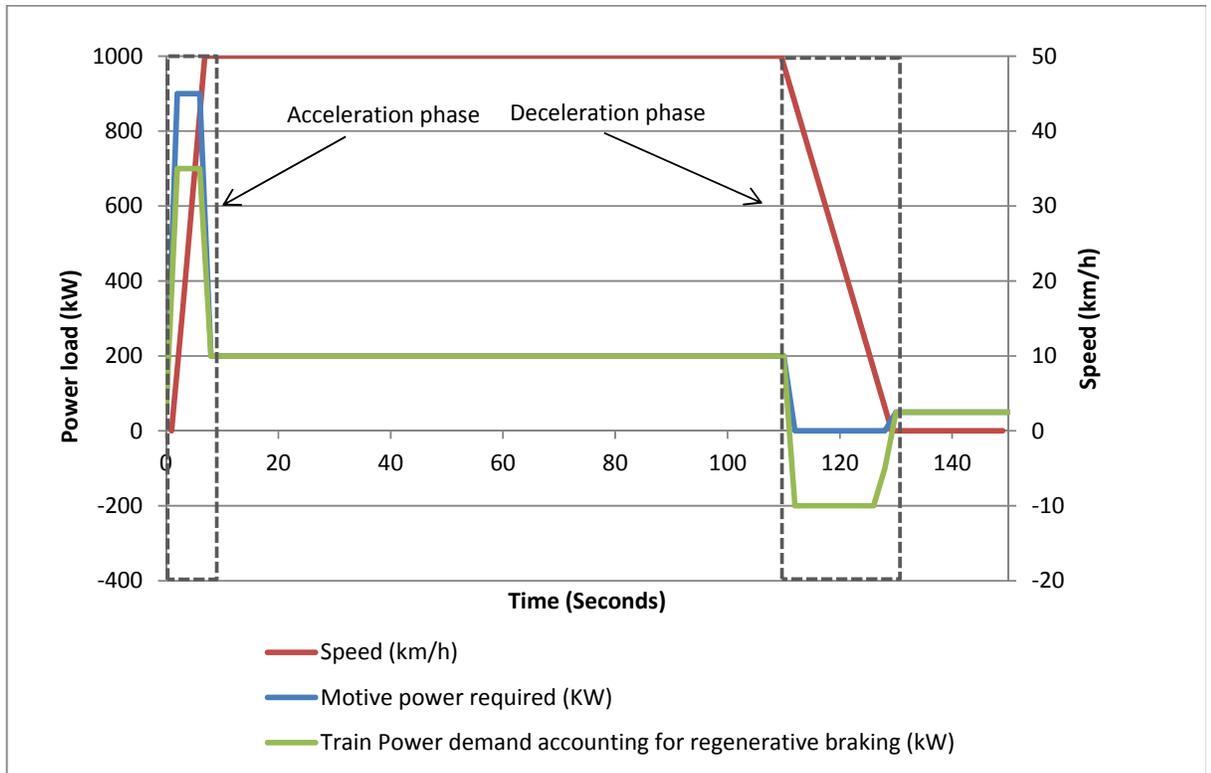


Figure 3: Light rail train power pattern VS speed pattern between two consecutive stops

The energy recovered during deceleration is larger than used for acceleration (even taking into account charge/recharge efficiencies). This remaining energy could be fed back into the catenaries thus reducing the total power required. However, this spare energy will not be available at all times, and the grid will still have to provide for the maximum power established in the following paragraph.

Based on the number of trains operating, the power demand profile shown in Figure 3, a spreadsheet was developed to estimate the power demand at all times during the day. With ten trains operating on the LRT line, with a shift of 9 minutes between each other, the maximum power demand (P_{max}) from the LRT system occurs when one train is accelerating, seven are cruising at constant speed and two are stopped. If the

catenaries losses are accounted for, the maximum power demand is therefore given by equation 3, and is 2.9 MW (3.2MVA).

$$P_{max} = ((P_{Accelerating} - P_{Regen}) + 7P_{cruising} + 2P_{Stop})(1 + L) \quad (3)$$

MVA (Mega Volt Ampere) is the most appropriate unit when discussing power on a transformer level. Multiplying by the power factor (0.9 for this study) allows conversion between MVA and MW.

P_{max} is the maximum power from the whole LRT line; it will be distributed on the 9 RTPS identified in Figure 2. Fendalton ZS is located in the central part of the line and may have to supply for up to 3 RTPS. In addition, the maximum load on Fendalton in 2010 is already high compared to its maximum capacity. For these reasons, it has been identified as the most impacted ZS. At peak time Fendalton would have to power up to 4 trains. Therefore the maximum power load from the LRT system on Fendalton ZS would be 1.3 MVA.

7. Results and analysis

Together with the impact each electric transport mode has on the local grid, a comparison between the two modes will be presented in this section. To enable a fair comparison, the EV fleet and LRT system must supply the same transport service. Each transport mode examined in this study can provide for a number of passenger trips per day. The number of passenger trips provided by EVs depends on the number of electric cars in Christchurch and the average number of passengers per vehicle. The number of trips provided by the LRT line depends on the trains' frequency and the average occupancy or load factor ratio. The Passenger kilometres travelled (PKT) provided each

day by the LRT system is calculated in below and the EV number is adjusted to provide for the same PKT.

The train network will provide for a number of passenger trips and passenger kilometres travelled daily. Orléans LRT provides 42,000 passenger trips each day distributed on 220 train journeys from one end of the train line to the other. By extrapolation, considering the frequency of trains travelling each day and the length of the networks in both Orléans and Christchurch, the Christchurch LRT network would provide 32,000 passenger trips per day. This number assumes that, despite a higher number of vehicles per person in New Zealand than in France (indicating a higher proportion of private vehicle use in New Zealand), commuting behaviour will be similar with respect to LRT patronage. The proposed LRT line follows a similar path through the Christchurch city as existing bus routes, and would provide a similar transport service. Thus, the national median bus trip distance of 5.5km (Ministry of Transport, 2010) is assumed for the proposed LTR. The daily passenger kilometres travelled (PKT) is therefore:

$$D_{PKT} = N_{trips} \times D_{Trip} = 176000\text{pkt/ day} \quad (4)$$

$$D_{PKT} = 176000\text{pkt/day}$$

With:

D_{PKT} : Daily distance per passenger in PKT

N_{trips} : The number of passenger trips provided by the LRT line each day: 32000.

D_{Trip} : The distance run for each light rail travel per passenger: 5.5 km on board.

The passenger kilometres travelled by an EV fleet depends on the number of vehicles, average daily commute and the average occupancy. Sullivan and O'fallon (2003) indentified an occupancy of 1.43 passengers per vehicle for Christchurch, and the average daily commute was 21.6 km (see table 3). Therefore, approximately 5700 EV would be required to provide 176,000 pkt/day, the same as the proposed LRT system. This translates to a 2.6% uptake of electric vehicles in Christchurch (meaning 2.6% of Christchurch private light vehicle fleet in 2010 being electric). All results presented from this point forward will now be directly comparable, providing the same level of transport services.

It is assumed that PHEV will dominate the market in the first stages of EV uptake as they offer more similarities with internal combustion engine vehicles and Hybrid vehicles. For an EV fleet with a majority of PHEV, daily EV charging lasts two and a half hour on average (see table 3). If all EVs are charging at the same time, the local distribution network will need to provide an additional power of 21.9 MVA. As shown in Table 1, the Fendalton substation would have to provide 11.9% of this load; thus would supply 2.6 MVA to charge a 2.6% EV fleet. Fendalton's spare capacity during winter peak time is already limited compared to other substation and the potential EV charging load in its catchment area makes it the most impacted substation in the event of an EV uptake.

The LRT system would run from 5am to 11pm with a maximum of 10 trains in service from 7am to 7pm. The maximum power demand for 10 trains was calculated to reach 3.2 MVA; 1.3 MVA of which would be powered by the Fendalton Zone Substation (see section 6.)

As the Fendalton zone substation is impacted the most by the demand of both the EV fleet and LTR system, Figure 4 shows the historic load of this substation on two different winter days in 2010. Figure 4a is the load on the 9th of August 2010; the day of maximum load for the year. Figure 4b is the load on the 30th of July 2010, in which the night time demand was the highest.

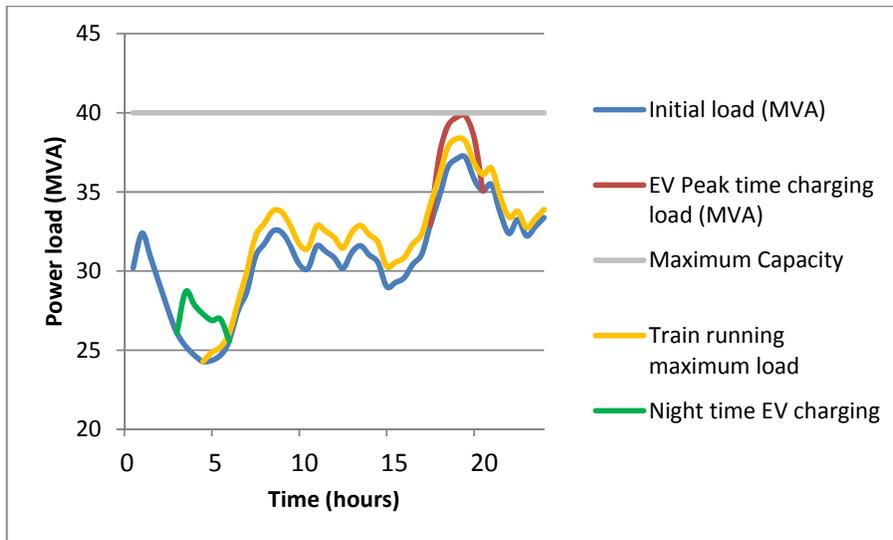


Figure 4a: Winter electricity peak day pattern on Fendalton with additional load if all EVs are charging after 6pm (9th August 2010).

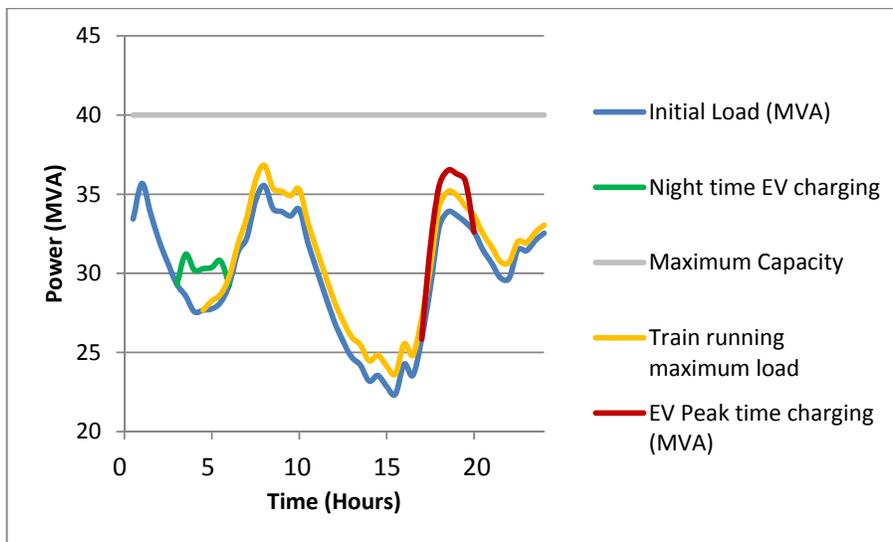


Figure 4b: Highest night time minimum day pattern on Fendalton with night time EV charging (30th July 2010).

Figure 4a shows that if a 2.6% EV fleet was charged after the last daily commute, the distribution substation with the highest number of EVs would reach its maximum capacity during winter peak demand time. On the other hand, if charging occurs at night time, only a small part of the substation spare capacity would be utilized. Figure 4b shows the benefits of shifting EV charging time to off peak hours. The chosen baseline day has the smallest night time spare capacity in 2010 (i.e. worst case scenario for night time charging). However, the EV charging load can easily be accommodated. By multiplying up the EV load profile, the spare capacity at night time in Fendalton on the 30th of July 2010 could allow an 11.5% uptake of EV in Christchurch.

These two graphs outline the benefit of EV night time charging. Without DSM, a 2.6% EV fleet in Christchurch would cause the Fendalton substation to reach its maximum capacity, whereas if charging occurred at night, even on the worst day of 2010, only a small part of the spare capacity would actually be used.

The LRT maximum load may be reached every 2-3 minutes throughout the day. However it would not affect the maximum capacity considering 2010 baseline loads. The LRT additional load in Fendalton can be sustained even during peak winter time. The local power distribution manager (Orion) load forecast predicts an 8.8% increase in peak load for the Fendalton substation between 2010 and 2020 (Orion 2011). Were the increase to be even each year, the maximum capacity would be reached in 2015 (instead of 2019) if the LRT was developed.

Table 6 provides a comparison between EVs and an LRT system and examines the total load on Christchurch for each system, the load required per passenger kilometre using

both modes, as well as the load on the most impacted substation. The energy from the LTR system is calculated by integrating the power demand for ten trains established in Section 6 at peak commuting times and fewer off peak time. Overall the energy required for the LRT line per day, and accounting for catenaries losses is approximately 32MWh. The energy per passenger kilometre is therefore close to 180Wh/pkt. Although this value is within the range of results reported for other cities (Newman and Kenworthy, 1999) it is towards the higher end of the range. This is primarily due to upper power values being used in specifying the train power requirements (to represent a worst case scenario for grid impact).

Table 6: EV and LRT comparison table

Parameter	2.6% EV Uptake	LRT line
Passenger kilometres provided daily	176,000 pkt/day	176,000 pkt/day
Median distance travelled each day	21.6 km	16.5 km
Average energy per passenger kilometres (losses included)	BEV: 209 Wh/pkt PHEV: 327 Wh/pkt	182 Wh/pkt
Additional load on the network at peak times	0 (with DSM)	3.2 MVA
Additional load on the network off peak times	21.9 MVA	3.2 MVA (LRT peak time can coincide with electricity peak time)
Additional power required per pkt	124 W	18 W
Additional load on Fendalton ZS	2.6 MVA (Off peak)	1.3 MVA (peak times)
Impact on forecast for the local distribution network	No change on 2010 forecast for upgrade	Upgrade required 4 years earlier than current forecast

The maximum power level required to supply an EV fleet is found to be 7 times higher than the maximum power lever required supplying a LRT providing the same transport service. However, EV charging allows for greater DSM opportunity as it can be carried

out at any time when the vehicle is parked. By minimising the number of EV owners charging during electricity peak times, the impact on the local grid could be reduced significantly and the local electricity network manager also gets an opportunity to utilise spare capacity, especially if charging is done during night time. The analysis shows that EVs are likely to be clustered in some areas of the city, resulting in some distribution substations providing greater power load for the EV fleet than others. Therefore, despite a significantly higher power and energy demand and a clear potential higher density of EV charging on a few substations, there would be minimal impacts given DSM opportunities.

An LRT system requires energy as it operates. Despite regenerative braking energy use and energy storage in embedded batteries, the trains will still require power at peak times. Only a few substations will power the LRT line and one substation may have to supply for 3 RTPS. The most impacted substation can supply the LRT system over peak time considering the previously described 2010 demand. However, local demand forecasts suggest that an upgrade will be required 4 years earlier than current plans.

8. Discussion and Policy implications

In preparing for the potential uptake of electric road/rail vehicles, previous research has examined generation and transmission issues, considering overall energy demand for both LRT and EVs or power demand at a regional or national scale for EV. This study builds upon this by examining the impact on a finer level, the local distribution grid; specifically the spatial location of increased power demand is examined, as well as the magnitude and timing of load.

Uncontrolled EV charging in Christchurch would result in several overloaded substations when more than 2.6% of the light private vehicle fleet is made up of EVs. Indeed, the spatial EV distribution predicted in this research shows that a few substations may have to supply the majority of the EV fleet if they were all charged from the owner's home after the days travel. However, relatively simple solutions already exists to avoid EV charging coinciding with peak electricity demand such as a ripple control system, already used for hot water heating in Christchurch. In addition, modern EV chargers will be programmable (Nissan Leaf, 2010b). Perfect DSM (in which 100% of the load is shifted to when electricity demand is at its lowest) could allow up to 11.5% of the private light vehicle to be EVs without any infrastructure upgrade. As one or more substations are demonstrated to potentially overload without DSM, proactive planning is recommended to ensure EV users would charge during off peak times. Such planning could include local authorities, or electricity retailers/suppliers, providing users with smart metering devices and activating a ripple control system. EV providers and household charger installers could also ensure the charger is programmed to charge off peak time only. An accurate prediction of the numbers and where EVs are likely to be charged would allow the best strategy to be implemented prior to EVs appearing in the market. In a recommendation for policy makers, it is suggested that due to the effects of clustering, attention should be paid to even a small number of EVs entering the fleet.

The analysis also shows that one LRT line could be sustained in Christchurch for a few years before infrastructure upgrades are required on affected substations. Therefore the power demand from the LRT system would not be evenly distributed either and

again one specific substation would provide for a significant part of the LRT load. Although the impact on the local grid is higher, the overall energy demand of a LRT system is lower.

In terms of power demand and time of demand, an EV fleet has the least impact on the local grid. Indeed, if managed properly, a large EV fleet (25,000 EV or 11.5% of Christchurch private vehicles) can be powered without any upgrade on the local grid, based on the impact on the substation serving the highest number of EVs. However, management relies on EV users to accept charging out of electricity peak time. This may not correspond to a natural use without any external incentive as commuters would tend to plug their car after the last daily travel and EVs would be charging during residential peak time. Therefore, more research must be done to identify the optimum DSM methods for EV users to reduce peak time charging. The LRT system should be managed by a separate private or public entity and the real power load will be easily predictable. Therefore although EVs seem a better solution in terms of power management, there is still a risk that the human factor does not behave as expected and this must be clearly considered as an unmanaged EV load could lead to power overloads.

In the case of Christchurch, both electric transport options were likely to have more significant impacts on the same power substations. In the event of the development of an LRT line, all the analysis regarding the electrical infrastructure required will be done before the projects starts. Regarding EV uptake, it is not planned where, when and to what scale the EV charging may happen. Therefore, the local distribution network manager must ensure these substations are identified and specific planning is done

accordingly. This will require the local electricity providers to understand when EVs could arrive in the local area and in what quantity. Furthermore, they should maintain a close relation with local authorities for the LRT. Finally it is important to understand daily electricity demand pattern for both electrified transport modes to ensure utilities can cope with peak demand.

9. Conclusion

Electric transport modes such as an LRT system and an EV fleet are power demanding systems and are likely to add significant pressure on the electricity system, including the local power utilities. This paper used Christchurch distribution network as a case study to highlight potential issues due to electric transport integration in a local area.

The analysis revealed that EVs in Christchurch would tend to be clustered and a small amount of distribution infrastructure would have to provide for a significant proportion of the EV load. A LRT line is supplied through RTPS evenly distributed along the line, but in the case of Christchurch, some distribution substations have to supply more RTPS than others. Therefore, in both cases, particular substations must supply with a greater proportion of the load, and in the Christchurch case study, it happen to be the same substation for the EV and LRT system.

Power demand from an EV fleet is significantly higher than power demand from an LRT line providing the same number of passenger kilometres per day. However, opportunities for Demand Side Management are much greater for EVs than a LRT system, resulting in an EV fleet having less of an impact. Without DSM an EV uptake larger than 2.6% of Christchurch private light vehicle fleet could overload at least one substation, whereas an 11.5% uptake could be provided for without any need for

infrastructure upgrade if charging occurs at night. DSM approaches for a LRT system include train embedded battery storage allow a reduction in maximum power demand. However, it is not possible to shift the demand to off peak times in this case as trains use the power while running and peak commuting demand coincides with electricity peak time. Therefore, several utilities would have to be upgraded earlier than current forecast due to the LRT additional load (four years earlier for the most effected substation). The impact of EV on the local grid could be insignificant if well managed, whereas LRT would require to upgrade some substations earlier than baseline forecast.

This research demonstrated that local distribution network can be significantly impacted by the introduction of electric transport modes. A LRT line will require several mega-watts at peak time and EV charging during peak time may overload several substations. These results clearly demonstrate that the unplanned introduction of electric transport would put the local distribution network at stake. Indeed, when the first EVs arrive in the city, measures should be in place to ensure EV users avoid charging during peak hours as a precautionary approach, should numerous EVs appear in the fleet later on.

Studies forecasting the level of integration for each transport mode at a local level are recommended to estimate potential power demand and to allow local electricity providers to adapt their infrastructures and services beforehand. Besides, predictions on EV impact on the grid highly depend on EV users' behaviour towards charging. Incentives to prevent them from charging over peak time must be carefully selected and social reaction to time of charging policy or price incentives for instance must be understood.

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