Assessing the potential impacts of electric vehicles on the electricity distribution network

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ABSTRACT

Despite the potential to deliver environmental, social and economic benefits compared with conventional, oil-fuelled vehicles, historically, electric vehicles (EVs) have not been commercially successful. However, improvements in battery technology and the development of electricity distribution network infrastructure seen over the last hundred years lend promise to widespread EV adoption. A transition to EV adoption will crucially hinge on successful integration into the existing electricity network. High-level studies have suggested that Australia could power all city and urban driving using existing off-peak electricity generation capacity. However, such studies give little indication of the ability of the current distribution network to charge EVs at particular locations, nor the impact on network operation. This paper investigates the impact of EV adoption on network loading and the potential to coordinate charging to best use existing network infrastructure. In particular, it reports modelling results from the deployment of EVs within a new distribution network simulation package. The results highlight the importance of charging coordination to minimise adverse operational impacts and network investment.

Keywords: demand management, electric vehicles, electricity distribution

INTRODUCTION

Australia depends on road transport for both commercial and private activities. In 2009, Australia's passenger vehicle fleet alone numbered over 12 million with an average annual growth rate of 2.5% (ABS, 2009). The national vehicle fleet is almost exclusively powered by carbon-dioxide emitting fossil fuels. The transport sector accounts for 14.6% of Australia's 541.2 Mt CO_2-e greenhouse gas (GHG) emissions (National Greenhouse Gas Inventory, 2009). Road transport makes up 12.7% of Australia's annual GHG emissions. Additionally, a range of gases and particulates including carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), and oxides of nitrogen (NO_x) and particulates (PM10) are also emitted. These are harmful to the environment and human health, causing petrochemical smog and contributing to increased respiratory illness. In Sydney alone, the annual health cost of these pollutants is $AU2-3 billion and results in twice the deaths attributed to road accidents (Kearney, 2006). Electric vehicles (EVs) eliminate these emissions at the point of vehicle use. Despite Australia's highly GHG-intensive electricity generation (36.9 % of annual GHG emissions), overall GHG emissions and other environmental impacts are also reduced (Simpson, 2009). A number of studies, including Scott et al. (2007) and Went et al. (2008) have also noted a trend to lower ownership costs compared with conventional internal combustion engine (ICE) vehicles. This trend is strengthened by the increasing and volatile price of oil.

EV technology has existed since the end of the nineteenth century (Wakefield, 1998). At that time however, the high cost of energy storage and absence of electricity distribution infrastructure prevented widespread EV adoption. This has been reinforced by ongoing investment in development of technological capacity and infrastructure for the competing ICE vehicle (Gagnon, 1999). However, this situation is changing with the emergence of lower cost lithium ion batteries. Australia, over the last hundred years, has also built an extensive electricity grid providing the previously missing distribution network. However, EV charging represents significant and mobile power and energy demand on residential and commercial distribution areas. Therefore, the successful adoption of EVs will depend on their capacity to integrate into the existing electricity network.

This paper first introduces stakeholders in planning and operation of Australia's electricity network, relevant earlier work and EV charging characteristics. It then presents an assessment of the impacts of adding EV charging to a single distributor and a distribution substation in Australia's electricity distribution network, the point where EV charging will occur. Implications of this additional load are discussed.

INTEGRATION OF EVS INTO AUSTRALIAN'S ELECTRICITY NETWORK

Electricity in Australia

Australians consume over 600 GWh of electricity per day (ESAA, 2009). This electricity is generated by private or state-owned entities that trade through the wholesale electricity market run by the Australian Energy Market Operator (AEMO). Electricity is transmitted to customers through a single, interconnected physical network. Planning for the network is conducted by Transmission (above 220 kV) and Distribution Network Service Providers (NSPs) in conjunction with AEMO. NSPs are monopoly businesses regulated by the Australian Energy Regulator (AER) to simulate competition (AER, 2009). Their role is to ensure that the network is able to reliably supply electricity. The nature of Australia's daily load cycle results in significant differences between peak and off-peak loading. Instantaneous supply-demand matching requires network infrastructure be rated for expected peak demand. Growth of this peak demand is a key driver for network investment. This leads to under-utilisation of network and generator assets, which could be exacerbated by EV charging, if added at times of peak demand. The flexibility of EV charging could also improve this utilisation.

Earlier Work

A number of studies from Europe and North America (Hadley, 2006, Kintner-Meyer et al., 2007, Perujo and Ciuffo, 2009, Scott et al., 2007) have supported off-peak charging of EVs as a way to provide the energy requirement for EV charging whilst limiting necessary generation and network expansion. An Australian study by Taylor et al. (2009) found that if 90% of Australia's peak annual capacity is available during off-peak, there is sufficient energy available over the network to support all city and urban passenger vehicle trips. This is an important result. However, it does not give any indication of the network's ability to supply the electricity to an EV at a particular point in the network. This will depend on the configuration and loading of the distribution network where the EV is connected.

Electric Vehicle Charging Characteristics

An EV is a vehicle that uses electricity, generally stored in a battery to power its drive system. EV charging depends on its charger power and battery capacity. As EVs are not yet widely available in Australia, there is little understanding of how EV owners will undertake charging. However, charging can only take place when the EV is parked and has access to power. These requirements are clearly met when parked at the owner's home overnight. Medium sized EVs are expected to have 160 km range and driving efficiency in the order of 156 Wh/km (25 kWh battery) (Perujo and Ciuffo, 2009, Letendre and Watts, 2009). IEC 61851-1:2001, the international standard for EV conductive charging permits single and three phase charging up to 16 A (3.7 and 11 kW) (IEC, 2001).

ASSESSMENT OF EV LOADING ON DISTRIBUTION NETWORKS

Modelling Method

Based on the conditions discussed above, an EV with 25 kWh/160 km battery charging at 16 A, single phase between 6 pm–8 am (while the EV is plugged in) was considered. This load was connected to a low voltage (230 V) network area feeding residential load. An 808 A, 11 kV/ 400 V distribution substation feeding three 400 A distributors, each supplying 60 houses (20 per phase) was modelled. Fuse protection at both substation and distributor levels was assumed. Applying a 1.25 fusing factor, the minimum load for which a distributor fuse will operate is 500 A. For analysis, maximum load was assumed to be at 75 % of element rating. These assumptions are taken from EnergyAustralia's network standard NS110 Design and Construction of Underground Residential Distribution. To ensure secure operation of the network essentially minimising supply interruptions, thresholds are set by the NSP to trigger investment. For this study, distributor and substation thresholds of 95 % and 100 % respectively were assumed. These reflect current NSP thresholds at this voltage level.

The effect of introducing EV charging was assessed for two standard residential network load cycles, Low Penetration Water Heating and High Penetration Water Heating. Both load cycles incorporate the use of off-peak network capacity to power electric hot water at different areas (and thus different rates of use) within Sydney's distribution network. Off-peak electric water heating is being phased out over the next decade through a joint state and federal government greenhouse gas reduction initiative (DEWHA, 2010). Results then reflect current impacts for both load cycles and potential network investment considerations when planning network upgrades for High Penetration Water Heating network areas. Winter peaking conditions were assumed. Load cycles were kindly supplied by EnergyAustralia.

1 – Single distributor: EV charging as conventional load

This scenario investigates the situation where EV charging is connected as a conventional load. Charging begins and continues until battery is full. EV adoption rates of 5, 25 and 50 % were considered reflecting one, five and 10 EVs per phase per distributor. Four distance categories, 20 km, 40 km, 80 km and 160 km were tested.

Although compared to Sydney's average per capita Vehicle-Kilometres Travelled (VKT) of 18 km (NSW Transport Data Centre, 2010), these distances are quite long, they allow assessment of likely as well as possible worst case charging requirements. This also makes the assessment more relevant to different locations in the network as expected driving distance varies with location (Transport and Population Data Centre, 2005). The effect of existing Time-of-Use (TOU) price signals in managing EV charging is also assessed, based on EnergyAustralia's Residential Smart Power energy tariffs (EnergyAustralia, 2010). Charing start times of 6, 8 and 10 pm reflect Peak, Shoulder and Off-Peak charging as these are the times that EVs are plugged in and the TOU price begins in the evening. The experiment parameters are shown in **Tab. 1** below.

Tab. 1: Scenario 1 Test variables

Residential Load Cycle	**Distance Travelled (km)**	**TOU Charging Regime**	**Adoption Rate (EV per phase, % per houses)**
Low Penetration Water Heating	20	Peak – 6 pm start	1, 5
High Penetration Water Heating	40	Shoulder - 8 pm start	5, 25
	80	Off-Peak – 10 pm start	10, 50
	160		

To assess additional loading impacts, the maximum load on the distributor and number of hours above trigger threshold were recorded for each Charging Regime.

Load Cycle: Low Penetration Water Heating

Fig. 1 below shows the additonal load resulting from 50 % EV adoption at 160 km.

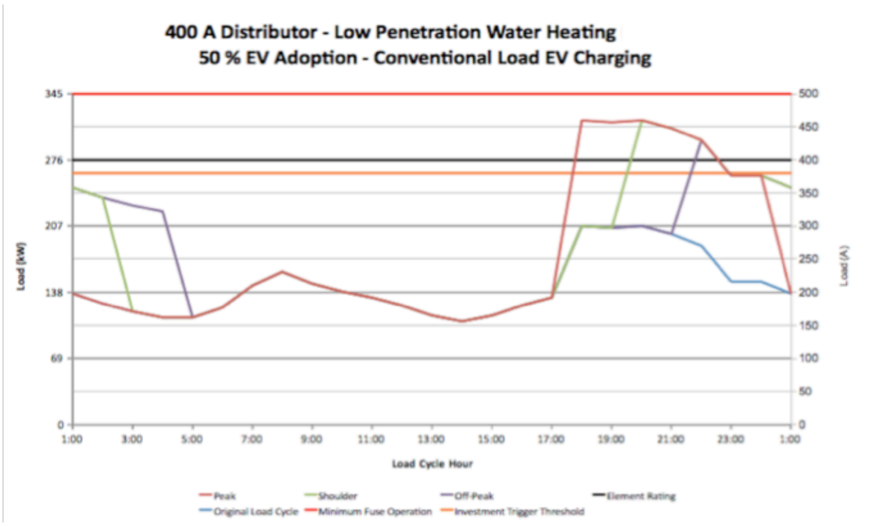

Fig. 1: Low Penetration Water Heating - Peak, Shoulder and Off-Peak Charging Regime – 50 % EV adoption 160 km scenario

For this scenario, Off-Peak charging has the lowest maximum load. This value exceeds the 95 % threshold trigger for network investment. The distributor rating (400 A) was also exceeded. This is not desirable, however, maximum load for this and indeed all charging scenarios would not result in fuse operation. Remaining results for the Low Penetration Water Heating load cycle are presented in **Tab. 2**. A comparison of maximum load values indicates that the magnitude of the new peak depends on the number of EVs charging and the Charging Regime but not on the distance travelled. This is a consequence of the original load cycle shape, which peaks first at 6 pm. Interestingly, the orignal load shape peaks again at 8 pm, when the Shoulder Charging Regime and pricing begins. This explains the similarities in maximum load between Peak and Shoulder regimes and suggests that Shoulder pricing is an insufficient price signal for minimising EV charging loading.

Tab. 2: Load Cycle: Low Penetration Water Heating EV charging Results

Charging Regime		Peak		Shoulder		Off-Peak	
Distance (km)	EV Adoption (%)	Maximum load (%)	Time above 95 % (Hr)	Maximum load (%)	Time above 95 % (Hr)	Maximum load (%)	Time above 95 % (Hr)
20	5	79	0	79	0	75	0
	25	95	1	95	1	88	0
	50	115	1	115	1	108	1
40	5	79	0	79	0	75	0
	25	95	1	95	1	88	0
	50	115	2	115	2	108	1
80	5	79	0	79	0	75	0
	25	95	2	95	1	88	0
	50	115	4	115	4	108	4
160	5	79	0	79	0	75	0
	25	95	2	95	1	88	0
	50	115	5	115	3	108	1

In assessing the urgency of the trigger, the Distance cateory becomes important. As Distance increases, so does the length of Time above 95 %. Operating above this threshold reduces safety margins that protect the network from surges. Comparison of Charging Regimes shows improvement with delayed charging start time.

Load Cycle: High Penetration Water Heating

Results found are similar to the Low Penetration Water Heating load cycle considered above. This is evident in **Fig. 2**, showing the 50 % EV 160 km scenario.

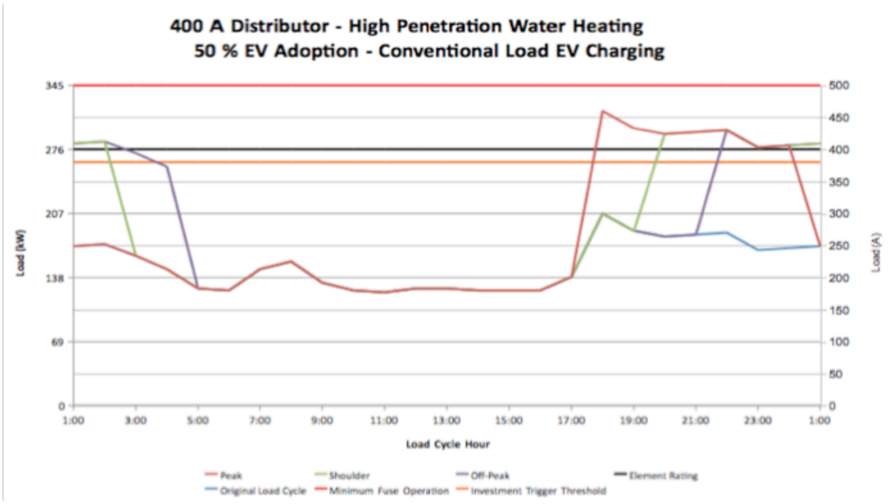

Fig. 2: High Penetration Water Heating - Peak, Shoulder and Off-Peak Charging Regime – 50 % EV adoption 160 km scenario

Although maximum load values in this case are generally slightly lower than the Low Penetration Water Heating case, the key difference between these load cycles is the length of operating time above the 95 % threshold. For the High Penetration Water Heating load cycle, these times are longer. Almost no improvement was found by delaying charging start time based on current TOU energy tariffs. This indicates for this load cycle, there is greater urgency for network investment planning to improve network safety margins if current TOU pricing is maintained. These trends also hold for shorter distances and are shown in **Tab. 3**.

Tab. 3: High Penetration Water Heating EV charging Results

Charging Regime		Peak		Shoulder		Off-Peak	
Distance (km)	EV Adoption (%)	Maximum load (%)	Time above 95 % (Hr)	Maximum load (%)	Time above 95 % (Hr)	Maximum load (%)	Time above 95 % (Hr)
20	5	79	0	75	0	75	0
	25	95	1	86	0	86	0
	50	115	1	106	1	106	1
40	5	79	0	75	0	75	0
	25	95	1	87	0	87	0
	50	115	2	107	2	107	2
80	5	79	0	75	0	75	0
	25	95	1	88	0	88	0
	50	115	4	108	4	108	4
160	5	79	0	75	0	75	0
	25	95	1	88	0	88	0
	50	115	7	108	7	108	6

From these results it appears that element loading could become a problem for distribution NSPs as EV adoption increases. This test, of course, represents an extreme case where all EVs charge simultaneously. If this were the case, network investment to allow for such loading would be significant. Results also show that there is scope to reduce loading problems by delaying charging start time, however, the existing Off-Peak price signal did not prevent load above the 95 % threshold. Essentially, the distributor could operationally cope with new EV load, but this load would need to be incorporated into network planning assumptions. A possible solution is to coordinated EV charging to minimise distributor loading. This may be necessary, particularly for higher EV adoption rates, to maintain safety margins for operation.

2 – Single distributor: Coordinated EV charging

This scenario investigates the extent to which EV loading on a 400 A distributor, initially loaded at 75 % capacity can be minimised by coordinating EV charging. For each time period, knowledge of instantaneous loading and charging distance for each EV were assumed. Charging Regime for each EV was determined based on this information under Peak, Shoulder and Off-Peak TOU price response.

Load Cycle: Low Penetration Water Heating

Compared to EV charging as a conventional load, coordinated charging significantly reduces distributor loading. The load curve resulting from adding 50 % EV adoption 160 km is shown in **Fig. 3** below. This was the charging scenario with the greatest impact identified above. Under a coordinated charging regime, EV charging is possible with a maximum load of 79 % (the same as the worst maximum load for conventional EV charging of a single vehicle), although higher loading is required when charging time is restricted to overnight Shoulder and Off-Peak TOU pricing. All other EV charging combinations could be completed with maximum load maintained at the initial 75 % maximum load.

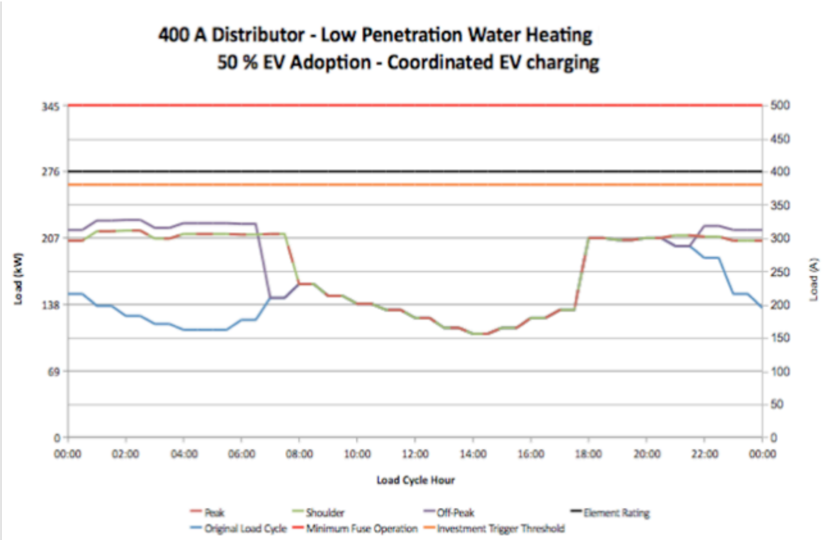

Fig. 3: Low Penetration Water Heating coordinated charging – 50 % EV adoption 160 km – maximum load can be maintained below 80 %.

Load Cycle: High Penetration Water Heating

Results were similar to those found for Low Penetration Water Heating. The load resulting from 50 % EV adoption 160 km is shown in Fig. 4 below. As for Low Penetration Water Heating, this was the loading with the largest distributor impact.

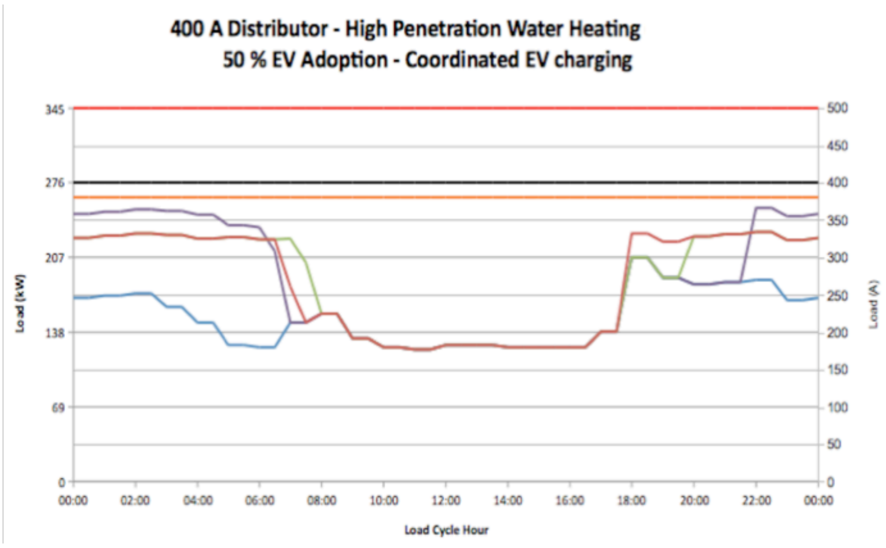

Fig. 4: High Penetration Water Heating coordinated charging – 50 % EV adoption 160 km – maximum load can be maintained below 83 %.

Under a coordinated charging regime, maximum load was restricted to below 83 %, less than the lowest maximum load for 25 % EV adoption charging. Again it is seen that higher loading is required for charging based on existing Shoulder and Off-Peak TOU pricing. With coordinated charging, all other charging combinations could be completed without exceeding 75 % loading. These results indicate that if coordinated charging is implemented, there is no longer a trigger for network investment. Further, the distributor utilisation is improved.

3 – Distribution Substation: Coordinated EV charging

To assess potential upstream network limitations for EV charging, coordinated charging algorithm was developed based on the 11 kV/400 V residential distribution substation feeding 60 houses per phase. Initial substation load (75 %) was divided equally between the three distributors. For each time period, EVs are charged based on rank (determined by charging distance required), TOU price signal response and network element loading. The resulting network load and EV characteristics were produced. This is shown in **Fig. 5** below.

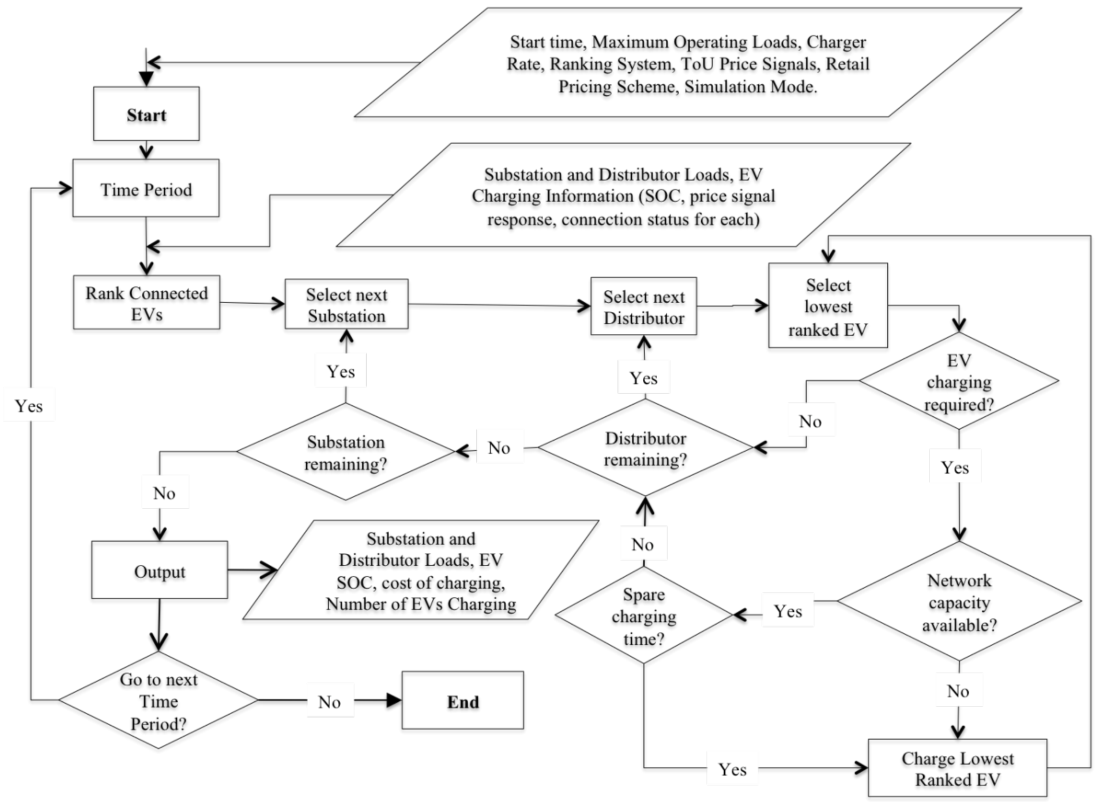

Fig. 5: Algorithm for determining network element loading and EV charging under coordinated EV charging

In this case, the network loading was limited by the substation capacity. For both Low and High Penetration Water Heating, maximum load was held at 75 % and the average resulting charging distance and corresponding state of charge (SOC) increase were obtained. Maximum load was then allowed to increase to allow 160 km (100 % SOC) charging per EV to be achieved. Results for 50 % EV adoption (10 EVs per distributor per phase) under Peak, Shoulder and Off-Peak Charging Regimes are presented in Tab. 4.

Tab. 4: Distribution Substation – Average EV SOC increase when coordinated charging is implemented to restrict network element loading greater than 75 %

Load Cycle	Charging Regime	SOC increase (%)	Equivalent Distance (km)	100% SOC increase possible	100% SOC increase maximum substation load (%)
Low Penetration Water Heating	Peak	61. 87	99	Y	89
	Shoulder	61. 87	99	Y	91
	Off-Peak	55.89	89	N	(100)
High Penetration Water Heating	Peak	46.14	74	Y	97
	Shoulder	45.67	73	Y	97
	Off-Peak	36.83	59	N	92.46% increase available at 100% loading

When maximum load is restricted to 75 % there is little or no difference in average SOC increase between Peak and Shoulder Charging Regimes for both load cycles. This shows that the price signal reflects the network loading. As charge start time is delayed with price signals, a trend to lower SOC increase holds for both load cycles. However, the lowest SOC increase would be sufficient to allow over 50 km of driving per EV. Given that daily VKT are generally lower than this value, the minimum SOC increase would satisfy most daily driving requirements without exceeding 75 % maximum load. However, this also shows that with higher EV adoption rates (or greater distance requirements), it may not possible to restrict charging to off-peak, as suggested in energy-based studies (discussed above). If this is the case, increased generation capacity and network augmentation may also be required.

The results in this section show that it is possible to coordinate EV charging to minimise network loading. However, for this coordinated charging regime to be implemented, the ability to remotely collect and analyse network loads and EV data will be required. The opportunity exists to incorporate these capabilities into future EV charging network infrastructure. A number of emerging businesses are taking this approach.

CONCLUSION

There are social, environmental and economic advantages in switching to EVs. However, charging EVs as conventional loads will increase maximum loading on distribution network elements. At significant deployment levels, this may accelerate network investment requirements. This impact may be reduced at low EV adoption rates if EV charging is delayed based on existing TOU Shoulder and Off-Peak pricing. If coordinating EV charging were implemented, this study suggests that it would be possible to minimise or eliminate these impacts without compromising expected daily driving distance at even the highest EV adoption rate examined.

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Anna Cain is an engineering student at the University of New South Wales. Her undergraduate thesis investigates the impact of electric vehicle charging on electricity distribution networks.