The role of electric vehicles in demand response: implementation, network impacts and market requirements

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Abstract: Increasing uptake of electric vehicles will put an increasing strain on underlying electricity grids. However, the negative impacts of electric vehicles can be mitigated by shifting charging to off-peak times, such as overnight, at no inconvenience to the end user. This paper presents the outcomes of an electric vehicle load control pilot demonstration undertaken in Victoria, Australia, that shows that centrally coordinated demand response of electric vehicle charging is a realistic possibility. Trial outputs are used to model the impacts of increasing numbers of electric vehicles on distribution networks. A load shifting solution is demonstrated to improve sustainable electric vehicle uptake in residential networks from 10% of households in the uncontrolled charging case to 80% of households in the controlled charging case. If the appropriate market and regulatory mechanisms are put in place to enable it, demand response for electric vehicles will significantly benefit both network operators and customers.

Keywords: demand response; load control; electric vehicles; real-world trials; smart charging; network impacts; market requirements; regulatory requirements; distribution networks; network constraints; optimal charging; spatial distribution.
The role of electric vehicles in demand response


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1 Introduction

Electric vehicles (EVs) are being promoted by many governments around the world, and most major automakers are actively developing fully electric and/or hybrid models for mainstream markets. Many reports suggest that electric vehicles are likely to gain increasing market share in the near future (Kinghorn and Kua, 2011; Paevere et al., 2012; Navigant Research, 2014).

The many potential advantages of electric vehicles are well discussed (decreased dependency on oil, reduced carbon footprint, desirable vehicle performance, etc.), but increased penetration of electric vehicles also introduces issues that must be carefully managed. An electric vehicle with a daily commute of 40 km puts the same demand on the electricity grid as a small household, so the contribution of electric vehicles to total demand and peak demand of electricity networks will be significant.

The role of electric vehicles in electricity networks is also well discussed: many studies and forecasts envision electric vehicles as significant network components that can have destabilising effects on the one hand, but can also be used as stabilising tools on the other: for example, for peak shifting in the form of vehicle-to-house or vehicle-to-grid generation (Kempton and Tomic, 2005; Sortomme and El-Sharkawi, 2011). Such load control forms part of an emerging philosophy in the management of electricity grids in which demand is matched to available supply, rather than the other way around, a process generally referred to as ‘demand response’ (Ipakchi and Albuyeh, 2009).
The amount that electric vehicles can contribute to electricity grid management is dependent upon the infrastructure that is available. Many countries are actively pursuing mandatory and widespread installation of advanced metering infrastructure (AMI). While not absolutely essential for distributed electric vehicle management, AMI can provide essential information and control mechanisms that enable much improved management of attached components. For example, smart meters with a communication interface can be used by network operators to centrally control vehicle charging as required.

One of the first trials worldwide of exactly such a system was recently demonstrated in Australia as part of the Victoria Electric Vehicle Trial (Angelovski and Handberg, 2013). Purpose-specific vehicle charge points were installed at several trial participants’ houses, and the network operator was able to control vehicle charging for a range of simulated scenarios. Post-trial modelling and analysis using data gathered during the trial provided a deeper insight into the implications of uncontrolled electric vehicle charging and the significant benefits arising from controlled charging.

This paper describes the technical end-to-end solution that was successfully demonstrated (Section 2), and discusses the implications of electric vehicle charging for electricity networks (Section 3). The main challenges for widespread implementation of load control appear not to be the technical ones, but rather the regulatory and market hurdles that exist; these are discussed in (Section 4).

It is demonstrated that centrally controlled demand response of electric vehicles is now a realistic possibility, that such central control can lead to significantly higher levels of sustainable electric vehicle uptake in distribution networks, and that the benefits to both network operators and consumers alike will be considerable.

2 Practical implementation

The state of Victoria, Australia, has recently seen the completion of one of the earliest and largest electric vehicle trials worldwide. The Victoria Electric Vehicle Trial was a 4-year, $5 million program that involved over 80 organisations across the full spectrum of stakeholders in the electric vehicle space, from original equipment manufacturers to fleet managers to network operators to policymakers (to name only a few). A key phase of this effort was a demand response/load control trial that brought together four partners:

- DiUS Computing, who developed the grid-integrated EV charging system and led the project design and delivery
- United Energy, an electricity distribution company who monitored and issued the load control events on the network where the trial took place
- The University of Melbourne, who provided post-trial modelling and analysis
- The Victorian Department of Transport Planning and Local Infrastructure, who coordinated the trial and provided logistical support.

This section describes the hardware, software, and communication protocols that were implemented to allow for central control of vehicle charging, explains the procedures involved in enabling a load control command to be realised, details the range of demand
response scenarios that were tested, presents their impacts in terms of communication performance and vehicles’ charging profiles, and discusses some of the challenges that arose in the practical implementation. For a full report on the outcomes of this trial, refer to Angelovski and Handberg (2013).

2.1 End-to-end system and components

The end-to-end system that was successfully implemented as shown in Figure 1 and consists of the following components:

1. A demand response system managed by the network operator (United Energy) that schedules and issues load control events
2. A customer portal that provides a user interface to access the smart meter network
3. An advanced metering infrastructure (AMI) mesh network that provides a wireless communication link between the network operator control centre and individual smart meters
4. The individual customer’s smart meter
5. The charge point itself (developed by DiUS Computing), which communicates with the smart meter via a home area network, connects to the electric vehicle and provides charging in a controlled manner
6. The ‘charging management system’: a suite of backend software tools that provide database and server support
7. A suite of customer interaction tools that notify the customer of intended charge events and enables their interaction and input
8. The electric vehicle.

Vehicles used in this study were operated as part of the Victoria Electric Vehicle Trial and included the Mitsubishi i-MiEV and the Nissan Leaf. Figure 2 shows an i-MiEV plugged into a DiUS charge point.

The full end-to-end system was successfully deployed and operated in eight project participant households.
2.2 System operation

Typical system operation is presented in Figure 3 and proceeds as follows:

1. **network operator scheduling**: load control events are scheduled in advance by the network operator in response to network operating requirements.

2. **network operator dispatch**: load control commands are issued to individual smart meters over the radio mesh network.

3. **charge point notification**: load control commands are delivered from the smart meter to the charge point via the home area network.

4. **charging management system notification**: load control messages are sent from the charge point to the charging management system (in this case, ChargeIQ) over a wireless connection on the cellular network.

5. **charging management system dispatch**: the charging management system delivers charge management event details through the website and smartphone application, and initiates message dispatch from the notification server to the customer’s nominated email account and phone number.

6. **customer notification**: any charge management event impacting vehicle charging is displayed on the relevant website and smartphone application.

Note that in this case the network operator and the third party charging manager were separate entities. In other countries, where network operation and charging management might be operated by the same entity, the above process could be simplified.

2.3 Load control events

For day-to-day charging management, all trial participants were able to choose one of two possible charging modes:
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- **demand charging**: also called ‘uncontrolled charging’, in this mode vehicle charging was initiated as soon as the vehicle was plugged in, and proceeded at the maximum possible charging rate until the vehicle was fully charged.

- **smart charging**: also called ‘off-peak’ or ‘time-of-use’ charging, in this mode vehicle charging only occurred between 11 pm and 7 am (in line with typical reduced electricity rates).

Smart charging was set as the default option, with users having the ability to opt-out (and choose demand charging) via the charging terminal, web portal, or smartphone application. However, only a small fraction of participants elected to opt out with most choosing to stay with the default, smart setting. A summary of all trial charge events is provided in Table 1.

**Figure 3** The sequence of events that unfold through the end-to-end system during a load control (LC) event (see online version for colours)

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Aggregated charging events for all households involved in this trial</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Charging activities</strong></td>
<td><strong>No.</strong></td>
</tr>
<tr>
<td>Smart charging events</td>
<td>365</td>
</tr>
<tr>
<td>‘On-demand’ charging events</td>
<td>291</td>
</tr>
<tr>
<td><strong>Total vehicle charging events</strong></td>
<td>656</td>
</tr>
</tbody>
</table>

To simulate typical scenarios that arise in network operation, two types of load control events were simulated:

- **Peak charge management**: on days when parts of the distribution network might be at risk of exceeding plant ratings (e.g., particularly hot summer weekdays), a utility load control event could be triggered. As this scenario can be predicted ahead of time, it would likely be possible to notify consumers 24 h in advance of the load control event. The duration of the event would cover the peak demand period of around 3–4 h, vehicle charging rates would be reduced by 50%, and consumers would be permitted to opt out with some accompanying cost impact.

- **Emergency charge management**: in rare situations under extreme weather conditions such as heat waves or lightning strikes causing unplanned or forced outage of a plant,
the network may require significant load reduction to avoid failure of remaining plants. For such events consumers may be notified only at short notice (10–15 min), events would take about 3 h, EV charging would be reduced by 100%, and participation would be mandatory.

Simulated peak and emergency charge management events were scheduled by the network operator, United Energy, at a variety of times and days, and participants received notifications in advance according to the nature of the event. A total of 64 load control events, split 50/50 between Peak and Emergency charge management, were delivered to eight household participants over four weeks.

Of these 64 events, six affected vehicle charging directly. On 28 occasions the vehicle was either not connected or already fully charged, and on 29 occasions the participant had chosen the default smart charging mode, and the emergency event took place outside of the overnight charging period. On three occasions the charge management event messages reached the smart meter, but failed to reach the charging terminal. One of the failed events coincided with an on-demand charge, and consequently the vehicle charged normally.

2.4 Trial outcomes

2.4.1 Communication

One objective of this trial was to assess end-to-end system response times – these are summarised in Table 2. Response times from the utility demand manager to the household smart meter were mostly within 5 s, with a lesser number of events taking up to 25 s. Response times from the smart meter to the charging terminal were generally instantaneous, although a small number of outlier events took much longer. The messages that had unexpectedly long response times were investigated as part of a post-trial analysis; for the most part these were owing to issues that are being resolved in the next generation of the DiUS charging system.

<table>
<thead>
<tr>
<th></th>
<th>Min</th>
<th>Max</th>
<th>Avg</th>
<th>Std. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smart meter</td>
<td>00:01</td>
<td>00:25</td>
<td>00:06</td>
<td>00:07</td>
</tr>
<tr>
<td>Charge point</td>
<td>00:02</td>
<td>42:17</td>
<td>01:39</td>
<td>06:46</td>
</tr>
<tr>
<td>Charging management system</td>
<td>00:02</td>
<td>50:03</td>
<td>9:40</td>
<td>15:46</td>
</tr>
<tr>
<td>End user applications</td>
<td>00:03</td>
<td>50:03</td>
<td>9:45</td>
<td>15:43</td>
</tr>
</tbody>
</table>

2.4.2 Vehicle charging profiles

A standard vehicle charging profile, as logged during this trial, is shown in Figure 4. In Australia typical voltage is 230 V, meaning that an electric vehicle draws up to 3.45 kW at a standard 15 A connection. The total load for the displayed charge event was 8.7 kWh.
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Figure 4  Typical charging profile for one of the electric vehicles in the trial (see online version for colours)

The charging profile of the same vehicle model, but during a peak charge management event, is shown in Figure 5. As can be seen, the peak charge management event successfully reduces the charging rate by 50%. The total load in this case was 9.2 kWh, but owing to the reduced rate charging took almost two hours longer.

Figure 5  Charging profile with a peak management event occurring from 20:00 to 23:00 (see online version for colours)

2.4.3 Customer acceptance

A qualitative survey was delivered to those who took part in the charging DM events. Although the limited number of responses (seven) suggests that the results be treated as anecdotal, some observations can be made as follows – Participants:

- received the Peak charge management event notifications, and where affected took steps to manage their charging/vehicle use
- were only occasionally aware that the emergency charge management events were taking place, and were largely unaffected
- were mostly accepting of load control by the utility, even if there were no financial benefits
• were less likely to accept mandatory load control, but could be influenced by a financial benefit
• found the SMS notifications to be the most useful of the user-facing applications.

2.4.4 Unexpected challenges

A noteworthy challenge involved a trial participant whose smart meter was installed in a common meter area at the entrance to their housing precinct. The charging terminal was installed at their parking location, which was separated from the smart meter by 20 metres and two brick walls. As an outcome, the charging terminal exhibited poor radio connectivity with the smart meter, such that the household was excluded from the load control aspects of the trial. In such situations, additional communication infrastructure would need to be installed to enable load control.

To conclude, where AMI is present, demand response for electric vehicles is a very achievable goal at the technical level. While there are several challenges that must be met (often unique to the networks in question), the technical solutions today exist to enable centrally controlled electric vehicle charging.

3 Network impacts and the case for controlled charging

The previous section demonstrated a successful end-to-end solution for implementing controlled electric vehicle charging. In this section, we show why it is desirable to implement such a system. A model of one of the neighbourhoods involved in the demand response trial was developed, and simulations of a range of further possible scenarios were conducted. This section discusses the potential impact of electric vehicles on electricity networks, describes the model and data used, and shows the outcomes of a range of simulated scenarios.

3.1 Network impacts

The vehicles in the trial drew up to 3.45 kW of power (using a 230 V, 15 A outlet). This is a fairly typical power demand for today’s commercial vehicles, with most drawing between 3.3 kW and 6.6 kW of power when slow charging at a level one connection at home (full charge of a typical vehicle battery from empty to full takes 6–8 h). Charging rates of fast chargers can be much higher, enabling a full charge in 30–45 min, but these are unlikely to be installed in residential homes for some time. While there are some residential loads with similar demand (e.g., air conditioners), electric vehicles typically need to charge continuously, for extended periods of time. A network having several electric vehicles therefore does not benefit from the possible diversity factor that results from on/off cycling of e.g., heating and cooling. As a result, electric vehicles are expected to be in many cases the most significant loads in residential networks. The concrete impact on the distribution network can consist of one or multiple of the following:

• Thermal overload of components. Distribution transformers and lines have nominal current ratings and capacity limits that should not be exceeded; if they are there is a risk of component failure or reduced asset lifetimes.
• **Voltage drop.** Both the network backbone and individual service lines have an impedance of their own, which means that houses at the far end of the network have a lower voltage than houses near to the transformer. As additional current for EV charging travels through these lines, the voltage at distant houses drops further still. Low voltage leads to overheating of motors and reduced lifetimes for home appliances.

• **Phase unbalance.** In many countries (such as Australia), power is provided three-phase with each house connecting to a single phase. When the three phases are balanced, there is minimal current in the neutral line and there are minimal additional losses. When the network is unbalanced, each phase can experience unexpected rises or drops in voltage and the neutral line carries more current (leading to greater losses, and contributing further to voltage drop). Large loads like electric vehicles can exacerbate this.

These issues are not unique to Australia, and multiple studies worldwide have found common problems (Kelly et al., 2009; Pillai and Bak-Jensen, 2010; Richardson et al., 2010; Lopes et al., 2011). Moreover, these issues are also not new to network operators and a variety of solutions exist:

• To address thermal overload of components, the governing philosophy is typically to size components according to the largest expected load. With high peaks owing to EV charging (and a high peak to base ratio), this means however that network assets may be oversized and underutilised.

• Voltage drop can be addressed by resizing networks and adding transformers. Alternatively, additional step-up transformers or low voltage regulators (LVRs) may be installed. Such measures are likely to be costly across extensive networks though.

• A degree of phase unbalance is inherent in almost all 3-phase networks. However, by carefully redistributing phase allocations at the distribution level (possibly also taking EV ownership into account), significant benefits can be achieved by network operators. This is a relatively low-cost solution that is now being pursued by many network operators.

However, most existing solutions to dealing with the increased peak of electric vehicles are likely to be costly, and that cost is ultimately borne by the consumer. But electric vehicles are also among the most flexible loads in residential networks; therefore there is much scope to reduce these costs by carefully managing the rate and timing of EV charging. As Section 2 shows, the technical solutions to achieve this exist; the benefits are further explored in the rest of this section.

### 3.2 Model, data, and flexibility of electric vehicle charging

The real-world trial presented earlier did not have enough participants to measure a truly significant impact on the network; instead further analysis of network stability was conducted in simulation, using a model of the network in question and simulation software packages POSSIM\(^1\) and MATLAB SimPowerSystems.

The network in question is shown in Figure 6. It is a residential network typical for suburban Australia and contains 114 houses with each house connected single-phase.
Exact phase allocation was not known, and had to be estimated using aggregated load data measured for each phase over a two week interval in August 2012.

Figure 6  Diagram of the neighbourhood in which smart charging was successfully implemented and further modelled (see online version for colours)

Total demand on each phase for a 24-h period in August 2012 is shown in Figure 7. As can be seen, there is significant unbalance inherent in the network, with a phase allocation on phases A:B:C of 50:43:21. Peak load occurs between 6 pm and 10 pm.

Figure 7  Total demand on a weekday in August 2012, for each phase in the network (see online version for colours)

To model vehicle arrival departure and the charging needs of each vehicle, existing data collected by the Victoria Department of Transport in a 2009 travel survey was used (Victorian Integrated Survey of Travel and Activity, 2009). This dataset contains 24 h vehicle travel profiles of several thousand participants, including both arrival and departure timing, as well as distances driven by each vehicle. The dataset was reduced to only those profiles originating from the neighbourhood that our network is located in, which left a total of 324 profiles that could be assigned to the vehicles in the study as required.

Using the travel distances and arrival/departure information available in the dataset, it was possible to calculate for each vehicle how long it would need to recharge after
arriving at home (assuming battery capacity and energy use typical of commercially available electric vehicles such as the Nissan Leaf). Figure 8 shows 24 h travel and charging profiles for 80 of the vehicles in this dataset. Average daily travel for vehicles in this neighbourhood is 37.7 km; as a result, average required charging time (assuming a 3.45 kW charging rate) is around two hours.

**Figure 8** Travel and charging profiles for 80 vehicles. The black overnight period demonstrates that there is significant flexibility regarding the timing of electric vehicle charging.

Importantly, however, this figure emphasises the flexibility available for electric vehicle charging. While the light grey areas (charging) coincide with peak demand (6 pm–10 pm, as shown in Figure 7), there is an enormous potential to shift this charging to the overnight period shown in black (when there is greater capacity in the network).

### 3.3 The benefits of controlled charging

How is such shifting of electric vehicle load achieved? The problem has received increasing attention over the past years, and several approaches have been proposed in the literature. For countries where there is no advanced metering or communication infrastructure, it is difficult to control vehicle charging centrally; in such cases distributed methods using local information are most applicable – some examples can be found in (Ma et al., 2010; Studli et al., 2012; Gan et al., 2013; Xia et al., 2014). On the other hand, where metering and/or communication is available, the problem may be solved centrally.
using maximum available information regarding the network and the vehicles that are charging – see e.g., Richardson et al. (2012), Luo et al. (2013), di Giorgio et al. (2014) and de Hoog et al. (2014a). The approach presented here falls into the latter category; as discussed in Section 2, smart meters are now installed throughout Victoria, and the technical solutions to enable centrally controlled charging already exist. It is likely that such infrastructure will become increasingly available in many parts of the world in the near future.

The specific approach used here is described in detail in de Hoog et al. (2014a). In short, electric vehicle charging is modelled as a receding horizon optimisation problem. The potential points of failure in the distribution network (thermal overload, voltage drop, phase unbalance) are modelled as constraints that must be satisfied. A full-charge target of 6 h is specified for each vehicle. The objective of the optimisation is to provide as much current to the vehicles as the network will allow. The full solution over the 6 h horizon is recalculated in discrete intervals, which means that vehicle arrival and departure, as well as changes in underlying conditions (such as fluctuations in household demand), can be taken into account.

**Figure 9** Uncontrolled charging scenario: (a) total demand; (b) voltage at most sensitive house and (c) typical charging profile (see online version for colours)

To demonstrate the benefits of load shifting, two scenarios are compared:

- In the **Uncontrolled** charging scenario, vehicles start to charge as soon as they arrive at home, and charge at their maximum possible rate until they achieve 100% state of charge (SOC).
In the **Controlled** charging scenario, vehicle charging rates are chosen by a central controller (for example the network operator), using the receding horizon optimisation method described above. As Section 2 demonstrates, such central control is a realistic assumption and has already been demonstrated in the real network.

For both scenarios, an electric vehicle uptake of 50% is assumed (in other words, every second household owns a fully electric or plug-in hybrid electric vehicle). While such levels of uptake are not expected for some time, a recent detailed study suggests that this may well occur in many neighbourhoods in Melbourne within the next 20 years (Paevere et al., 2012).

Figure 9 shows the outcome in the uncontrolled case. Since many vehicles arrive at home and start charging during peak time, a new, much higher peak load occurs (Figure 9(a)). Even though many network components can sustain high peaks for short periods, the limit of 130% of transformer capacity (dotted red line) is significantly exceeded. Voltage at the most sensitive house in the network drops significantly below the minimum required level (Figure 9(b)). However, the vehicles charge at their maximum rates and achieve full SOC quickly: Figure 9(c) shows the charging profile of a vehicle that departs home at 9 am, returning home at 5 pm with an initial SOC of 50%.

Figure 10 shows the outcome in the controlled case. The assumed upper limit of 130% of transformer capacity is respected, and thermal limits of all network components are not exceeded (Figure 10(a)). Voltage at the most sensitive house stays within required limits (Figure 10(b)). Vehicle charging rates are somewhat reduced during peak time, and occasionally interrupted (Figure 10(c)). However, all vehicles are fully charged within 6 h.

While the results presented here are specific to the 50% uptake case, a wide range of further scenarios were explored in simulation. These can be summarised as follows:

- If vehicles are left to charge in an uncontrolled manner, then network failures already occur in many cases at EV uptake rates of only 10–15%. In most cases, low voltage is the first point of failure. This is in line with several other international studies, e.g., Kelly et al. (2009), Pillai and Bak-Jensen (2010) and Richardson et al. (2010).

- If vehicles are charged in a controlled manner, then very high uptake rates are sustainable. In our simulations a wide range of vehicle travel profiles and vehicle assignments to houses were simulated; even at uptake rates of 80%, the controlled method allowed for all vehicles to be charged within 6 h, in all cases.

In other words, almost every household in this neighbourhood could own an electric vehicle and, assuming controlled charging, **no further network upgrades would be required.** Clearly the implications are significant: controlled charging leads to much higher utilisation of network assets and significantly deferred network augmentation. Given that required network upgrades in the uncontrolled case would require significant investment (more on this in Section 4.1), the savings per consumer are evident. A more detailed analysis of the financial implications is the subject of ongoing work.

It should be noted that these results only show the impact of load shifting; with vehicle-to-house or vehicle-to-grid generation, the possibilities for efficient network utilisation are considerably greater still.
3.4 Local network constraints

Another outcome of the modelling exercise was a closer examination of the active constraints in the low voltage distribution network. Two unexpected findings emerged:

1. Spatial distribution of loads is very important towards determining network stability. Adding vehicles in sensitive locations of the network can have an order of magnitude greater impact than adding vehicles at robust locations. The most sensitive locations are typically the houses farthest from the transformer on the most heavily loaded phase (although individual service line parameters and lengths, as well as distributed generation or storage, can skew this picture). In a separate study using the same network described in Section 3, a single vehicle charging at a sensitive location in the network was determined to have the same impact on minimum voltage as 45 vehicles charging in more robust locations (de Hoog et al., 2014b).

2. Closely related to the above, individual customers in a given distribution network can be very closely coupled. An example is provided in Figure 11. In this network, the lowest voltage occurs at house 20. The highest voltage occurs at house 19, the house right next to it. This is due primarily to the neutral point shift and neutral line current that results from this network being heavily unbalanced. The impact however is that situations may arise where the ability of an owner to plug their vehicle in at house 20 is highly dependent on whether the owner at house 19 is also charging: it could happen for example, that house 20 needs house 19 to be charging, to restore
sufficient phase balancing for house 20 to be able to charge. (When the owner at house 19 plugs in, he or she restores some phase balance by adding load to the most lightly loaded phase, bringing voltage back up on the heavily loaded phase). These curious effects are the subject of ongoing work.

These results suggest that local network constraints play a very important role in determining a network’s capacity for charging electric vehicles, and should therefore not be overlooked.

Figure 11 Demonstrating the close coupling between individual households resulting from phase unbalance (see online version for colours)

4 Regulatory and market requirements

Section 2 presented an end-to-end solution for controlled electric vehicle charging, and Section 3 demonstrated the significant benefits that would result as regards the underlying distribution network. With controlled charging, the network may be better managed and augmentation is significantly deferred. But, a real implementation is only possible if the regulatory and market environments to enable it are in place. Customers do not like the idea of mandatory load control and network operators may not have the proper incentives to push the case for controlling it in the first place. This section explores the regulatory and market requirements that are necessary to enable this transition.

4.1 Business case

To understand the business case for demand management of electric vehicle charging, it is necessary to understand the benefits arising from controlled charging in financial terms. These are considered here for a single distribution network (i.e., a neighbourhood of approximately 100 households).

4.1.1 Cost of not implementing demand response mechanisms

As the modelling in Section 3.3 indicates, at electric vehicle uptake rates of 10–15%, some form of network augmentation is required if the operating parameters of the network are to be met. High-level costings for this augmentation can be understood in terms of the following options:

- Transformer upgrade/additional transformer – estimated costs may be $AUD 50,000–60,000 for a pole-mounted unit, or $AUD 100,000–120,000 for a ground-mounted kiosk. Note that this option is applicable in a location where there is high voltage (HV) infrastructure available; if not, estimated costs rise to $AUD 150,000–200,000 owing to additional cable requirements.
• Low voltage regulator (LVR) installation – estimated cost $AUD 150,000-170,000. This option should be applicable in a location where there is no HV network available to install a new transformer. United Energy is currently trialling this new LVR technology on its network.

4.1.2 Cost of implementing demand response mechanisms

Controlled charging would allow over 80% of households to adopt electric vehicles without negative impacts on the network. No network augmentation would be required; instead the end-to-end solution described in Section 2 would need to be implemented. Assuming a cost of $AUD 600 per grid-integrated charging unit, for a neighbourhood having 10% electric vehicle uptake the total cost would thus come to around $AUD 7000. Note also that this estimate captures the entire cost of the dedicated EV charging units, not simply the utility load control functionality.

A comparison between the two results provides a clear business case in favour of the demand managed approach: assuming 10% electric vehicle uptake this can be approximated as around one 10th the cost of the uncontrolled charging scenario, on a per-customer basis.

While this analysis appears to present a compelling argument in favour of demand management of electric vehicle charging, the findings in Section 3.4 highlight a tension that may have implications for the business case assessment. Local network impacts from vehicle charging vary significantly from house to house – for charging activities undertaken independent from each other and through their interaction. This creates a potentially significant sensitivity that may reduce the effectiveness of demand management programs that reflect higher-level network constraints alone.

4.2 Market arrangements

Despite the clear business case, existing Victorian market arrangements suggest that significant barriers may exist for implementation of the demand management (DM) solution (Productivity Commission, 2013). The benefits associated with investment in DM technology are spread across the electricity market – generators, transmission and distribution businesses, retailers and end-users. As a result, no one market participant can realise all the benefits from investment in DM, a problem known as ‘split incentives’:

• Victorian electric vehicle drivers have little incentive to invest in ‘grid-integrated’ charging technology capable of being remotely controlled by the network operator.

• For Distributors, there are persistent doubts relating to the reliability of DM performance by consumers as a means for addressing network capacity constraints (this issue is discussed further in Section 4.3).

• For third-party aggregators, the transaction costs associated with contracting a critical mass of residential customers are a deterrent.

In addition, owing to the emphasis on network solutions based on capital expenditure, the Australian market rules currently disincentivise distribution businesses from investing in DM (Headberry Partners and Bob Lim & Co., 2008).

Despite these challenges, opportunities for grid-integrated DM of electric vehicle charging exist within the current market arrangements:
vehicle charging loads are both significant and transferable within the large windows of opportunity that exist when the vehicles are parked/plugged in, making them well-suited to DM

vehicle drivers may be obligated to work with their Distributor on integration of EV charging loads into the system (United Energy, 2013)

as part of the rate review process, distributors may be obliged to consider DM alternatives to network augmentation in support of vehicle charging demand (AEMC, 2013; Productivity Commission, 2013)

electricity utilities may promote vehicle uptake as a means of promoting electricity demand/revenue (Parkinson, 2013)

the Australian market rules allow distributors to propose innovative tariff arrangements as a means of promoting vehicle uptake (AEMC, 2013).

While rule-makers offer a Demand Management Incentive Scheme in Victoria, Distributors sought approval of $AUD 550,000 of expenditures in 2011 – equivalent to only around 5% of the allowance (Australian Energy Regulator, 2012). In a contrast that has been explained in terms of the disaggregated character of the Victorian electricity market (Headberry Partners and Bob Lim & Co., 2008), the three main Californian network operators had $USD 1 billion in (analogous) Demand Response program expenditure approved for the 2012–2014 period (California Public Utilities Commission, 2013).

This disparity in uptake suggests that the market settings associated with demand management (response) may be the strongest influence on adoption of fully grid-integrated electric vehicle charging.

4.3 Program design

A key challenge for adoption of grid-integrated electric vehicle charging lay in program design effectiveness, particularly from the perspective of both utilities and regulators.

Crucially, regulation to promote efficient market operation should distribute costs and benefits appropriately among key stakeholders and address the issues set out in Section 4.2. Specifically, market mechanisms should exist to:

- promote investment decisions that favour DM-capable vehicle charging infrastructure over the non-DM alternative, for example through utility ownership of charging infrastructure, the provision of rebates for approved equipment, or via regulation of the technical requirements for grid connection; and

- share the avoided investment benefits from vehicle charging activities undertaken in line with network demands/constraints, for example through market rules that relate to demand response at the residential level.

These are issues which at the high-level are dealt with in market rules that relate to demand management more broadly. However once these mandatory requirements have been addressed, actual program effectiveness may be strongly influenced by considerations outside of the market arrangements.
Anecdotal results from this project indicate that electric vehicle drivers may accept load control, even without a financial incentive. However, they may be less likely to accept mandatory load control – an observation also made elsewhere (Dahlenburg, 2012). For distribution businesses, peak load management must be sufficiently reliable to justify this approach over network augmentation. This would favour mandatory load control as a preferred option in contrast to the preferences of drivers.

Although these observations suggest a natural tension that will work against DM program effectiveness, other insights promote confidence in the DM approach:

- peak demand periods are typically infrequent and short-lived (Productivity Commission, 2013)
- price signals that clearly disincentivise charging during peak demand periods are likely to be effective at promoting cooperation by most electric vehicle drivers, even allowing for the presence of an ‘opt-in’ option
- timely, relevant and reliable information about DM events is likely to promote acceptance and cooperation by vehicle drivers
- real-time, remote monitoring and control capabilities for vehicle charging allow drivers to easily and conveniently respond to DM events
- modelling (Section 3) indicates that up to 10% of drivers may choose to ‘opt-out’ of a utility DM event before network capacity becomes an issue.

These insights sit alongside the experience gained through the wide range of direct load control programs are already being offered by US utilities (Clearly Energy, 2013). Furthermore, electric vehicle uptake is likely to be gradual, such that refinement and validation of the program design can occur over time. This is consistent with recommendations on demand response program design more generally (Massachusetts Institute of Technology, 2011).

4.4 Additional considerations

While this paper has focused on the specific issue of demand management of electric vehicle charging in the residential context, the implications for other scenarios should also be considered.

Vehicle charging activities outside of the home, for example in the workplace, also have the potential to contribute to peak demand impacts. These events will not be addressed through traditional demand response programs that centre on the home, entailing that alternative management strategies be considered:

- workplace or fleet charging infrastructure should be DM-capable in commercial/industrial sites that are current or future candidates for participation in demand response programs
- arrangements that support electricity markets of the future including ‘prosumers’ and Virtual Power Plants should consider options that would recognise vehicles no matter where they plugged into the network.

Vehicles as storage (e.g., Vehicle-to-Grid/V2G) is another foreseeable technology development with relevance to this discussion. While the market arrangements that
relate to energy storage more broadly will provide the framework for vehicle-specific considerations, detailed program design will likely draw on insights from vehicle charging DM such as those presented in Section 4.3.

5 Conclusion

A pilot demonstration of centrally controlled electric vehicle charging was demonstrated as part of the Victoria Electric Vehicle Trial. In this demonstration, load control commands were issued by the network operator in response to simulated emergency and peak management scenarios. The commands were successfully communicated to electric vehicle charge points via existing metering infrastructure, and electric vehicle charging was interrupted or reduced as required.

A post-trial modelling exercise examined the potential advantages of controlled electric vehicle charging. Using real network models and real demand and vehicle travel datasets, it was determined that in an uncontrolled charging case (when vehicles charge as soon as they are plugged in), problems arise at vehicle uptake rates of only 10–15%. With a controlled method, this uptake could be boosted to 80%, enabling much improved network utilisation and offering the opportunity for significantly deferred network augmentation. The modelling exercise also demonstrated the importance of spatial distribution of loads and the unexpected network constraints that can occur in unbalanced three-phase networks.

Trial participants were mostly open to the idea of controlled charging, although mandatory controlled charging was less attractive. Given the existence of a demonstrated solution, obvious benefits to network management, and a customer base that is willing to adopt controlled charging, the main challenges in widespread implementation therefore lie in the regulatory settings and market arrangements. The existence of measures that incentivise demand management more generally are the starting point for these considerations.

However, if these barriers can be overcome, then controlled electric vehicle charging offers benefits to all players involved. With the increasing possibilities for the use of electric vehicles as distributed storage devices, providing vehicle-to-house and vehicle-to-grid generation as required, the benefits to network management and end users are likely to be more significant still.

References


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Note

POSSIM: POwer Systems SIMulator, developed at the University of Melbourne. POSSIM is a C++ based wrapper that uses MATLAB SimPowerSystems for model development and load flow analysis.