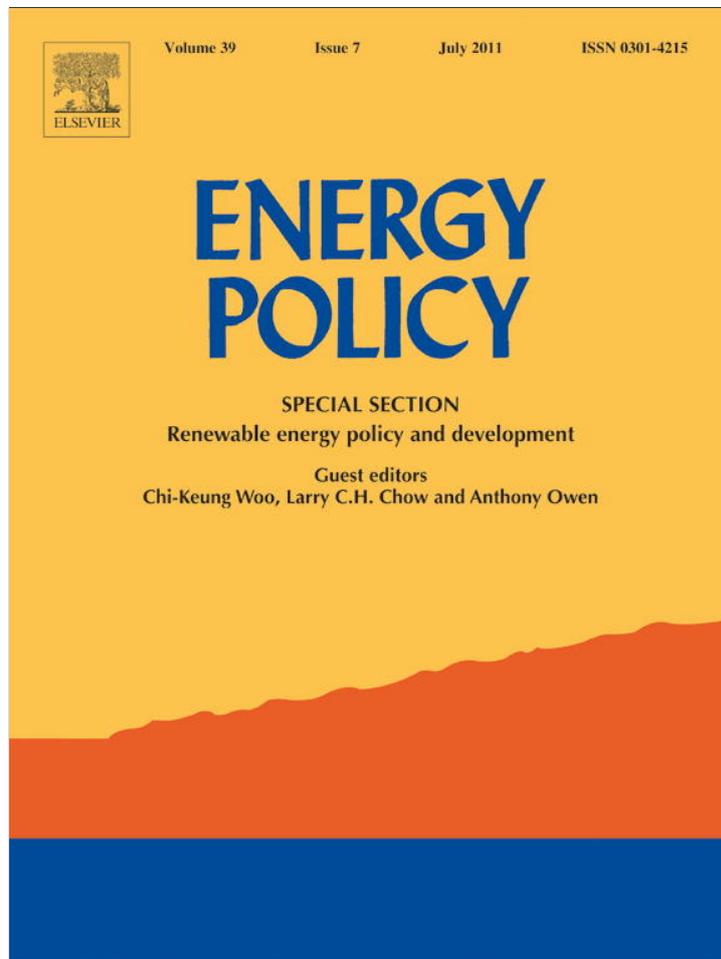


Provided for non-commercial research and education use.  
Not for reproduction, distribution or commercial use.



This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

<http://www.elsevier.com/copyright>



## Modelling the impacts of electric vehicle recharging on the Western Australian electricity supply system

Jonathan Mullan<sup>a,\*</sup>, David Harries<sup>b</sup>, Thomas Bräunl<sup>a</sup>, Stephen Whitely<sup>a</sup>

<sup>a</sup> School of Electrical, Electronic and Computer Engineering, 35 Stirling Highway, The University of Western Australia, Perth, Western Australia 6009, Australia

<sup>b</sup> Research Institute of Sustainable Energy, Murdoch University, South Street, Perth, Western Australia 6150, Australia

### ARTICLE INFO

#### Article history:

Received 10 January 2011

Accepted 21 April 2011

Available online 10 May 2011

#### Keywords:

Electric vehicle

Electricity demand

Utilisation

### ABSTRACT

This study investigates the potential impacts of EVs on the Western Australian electricity grid, the constraints on the system's capacity to supply electricity for EV recharging and the options for managing those potential impacts and constraints. Western Australia is geographically isolated and the electricity network has no interconnection with neighbouring regions. The State energy and vehicle markets are independent of issues occurring in neighbouring states. Western Australia is a relatively clean sample space. This study eliminates uncertainty in vehicle adoption rates from analysis by assuming that all new vehicles are EVs. This gives a worst case scenario in terms of load growth and shows that it will over 200,000 EVs, which represents 10% of the fleet, before there is any significant impact on peak demand even if charging behaviours are left unfettered. The study also shows, however, that the electricity supply and transmission industry can achieve significant short- and long-term benefits if vehicle charging behaviours are managed from the outset, through, for example, demand management or structured tariffs. In the short-term, providing incentive for off-peak recharging increases utilisation of existing transmission capacity, and cheaper, more efficient base-load generation infrastructure. In the long-term, investment in more underutilised capacity can be avoided.

© 2011 Elsevier Ltd. All rights reserved.

### 1. Introduction

The ability to rapidly accelerate the take-up of electric vehicles (EVs) will be determined to a large degree by the capacity of the local electricity industry to generate and transmit the power required to recharge vehicle batteries. The focus for many has been centred on whether the electricity supply infrastructure can cope with EV adoption growth (Book et al., 2009; Hunt, 2008). Over the long term, supply can always be increased to meet a slow demand growth. It is a fast, and perhaps unforeseen, short-term growth in power demand due to electric vehicle penetration that is of concern.

The results of these studies are therefore highly reliant upon and sensitive to the assumed EV adoption rates. While many forecasts on EV take-ups have been made (Graham et al., 2008; Book et al., 2009; Cunningham, 2009; Hodson and Newman, 2009; Lache et al., 2008; National Research Council of the National Academies, 2009), the global financial crisis (GFC) and the Japanese earthquake and tsunami have since brought about

significant uncertainty in both underlying demand and the availability of the necessary investment in EV manufacturing capacity. While many large and small vehicle manufacturers are bringing EV models to market in the next 2–5 years, little information has been made public regarding production numbers. In light of this, this study eliminates vehicle adoption and production from the analysis by assuming that all 90,000 new vehicle sales are EVs. This is the extreme case given that in 2008 first generation hybrid electric vehicle sales accounted for just 0.53% of the new car market in Western Australia and 0.64% across the whole of Australia (Federal Chamber of Automotive Industries, 2009). By taking this approach, this study seeks to establish how many EVs it will take to become problematic or beneficial under various charging behaviours over time.

This study investigates the potential impacts of EVs on the Western Australian (WA) electricity grid, the constraints on the system's capacity to supply electricity for EV recharging, and the options for managing those potential impacts and constraints. Western Australia is geographically isolated and the electricity network has no interconnection with neighbouring regions. The State energy market is not impacted by activities and issues occurring in neighbouring states. Western Australia therefore remains a relatively clean sample space.

Electric vehicles will represent an additional new load that is very different to other loads in that it is mobile. The instantaneous

Abbreviations: EV, electric vehicle; GFC, global financial crisis; PHEV, plug-in hybrid electric vehicle; REV, renewable energy vehicle; SWIS, South West Inter-connected System; UWA, University of Western Australia; WA, Western Australia

\* Corresponding author. Tel.: +61 421 122 985; fax: +61 8 9276 6795.

E-mail address: [jmullan@optusnet.com.au](mailto:jmullan@optusnet.com.au) (J. Mullan).

load impact of recharging the battery pack of a single electric vehicle using standard electricity supply infrastructure would be similar to that of a 1.5 kW air-conditioning unit. This is an interesting comparison for a number of reasons. As a new source of demand that proliferated quickly in the residential market in recent decades, the local supply industry faced a number of challenges due to the resulting change in the magnitude and time of peak demand (Office of Energy, 2004; George Winkelfeld and Associates, 2004). Air-conditioning is the one existing residential load that has been targeted by the electricity industry across Australia in the past decade, trialling demand management schemes whereby grid operators have control over air-conditioner compressors (Office of Energy, 2004; ETSA Utilities, 2008). Recharging EVs are a mobile load and where the load impacts the network will depend on where a vehicle is parked—whether in garages at home overnight, and during the day spread across suburbia, in shopping centre car parks and in public car parks located in and around the business and industrial centres.

The greater the charger rating, the larger the burden on the local electricity distribution and transmission networks, albeit for a shorter duration. One recent development is the deployment of Australia's first fast-charging network, comprising 12 Level 2 fast chargers in the Perth metropolitan area, each representing a 7.7 kW load, as part of a wider EV field study, the Australian Research Council (ARC) Linkage project on "Analysis and modelling of driving patterns for limited-range electric vehicles". This study is being undertaken by the University of Western Australia (The REV Project, 2010) and Murdoch University together with a number of industry partners. The goals of this charging trial are to find out when and where electric vehicles will be charged and how tariff structures will affect user charging behaviour.

This trial will also give statistical data on charging station requirements, which can then be used for predicting future required charging station infrastructure requirements such as numbers, location, distribution network capacity, and energy requirements for larger EV fleets.

As a positive side-effect, this trial will help to break the chicken and egg status quo in providing an early supporting infrastructure to EV owners in the first wave of commercially produced EVs, expected to be available in 2013.

It is reasonable to assume that as the EV market matures and battery technologies capable of faster charging are introduced, there will be a demand for higher powered charging equipment in the home and distributed across the metropolitan regions. Using a Level 3 recharging system would increase the load accordingly. If a high powered 3-phase charger is used, this load would be equivalent to a number of houses appearing on the network for as little as an hour a day, which has ramifications for peak demand and network utilisation.

Understanding the implications of this new potential load will be critical to the management of behaviour and the planning of electricity generation, transmission, and distribution capacities over coming decades. A new source of demand, such as EV recharging, is likely to have a pronounced impact on future demand. The extent to which a system can cope with the change is dependent upon whether poor charging habits are allowed to develop as well as the rate of adoption, which may be accelerated by government, economic, or resource pressures.

Several published studies of the potential or likely impacts of EV loads on local grids have been undertaken in the USA (Morrow et al., 2008; Marfisi et al., 1978), and the UK (Hunt, 2008) and the findings obtained from some of these studies are discussed below. Few, if any, such published studies have been undertaken in Australia to date. Field trials will yield useful information on EV charging. Australia's first field trial of Electric Vehicles is the Western Australian Electric Vehicle Trial, launched in March 2010

(The REV Project, 2010; Co2Smart, 2010). This trial encompasses the conversion of 11 Ford Focus cars to electric drive by local companies, supervised by REV/UWA, and managed by Perth start-up company CO2Smart. The converted EVs will be placed in regular government and industry fleets. This trial will show whether and to what degree limited range and extensive charging times will affect the usability of these cars. It will also give first answers to questions regarding service requirements, special considerations during roadside assistance, etc. All vehicle movements and charging operations are being monitored by black boxes with GPS, charging and power usage sensors, as well as through a web-based online telemetry system developed at UWA.

While some useful lessons can be learned from studies undertaken overseas of the potential or likely impacts of electric vehicles on grids, many of the underlying assumptions of those studies are not always, or totally, applicable to the other situations. Electricity supply systems and load profiles vary significantly from one place to another. In cold climates, where a significant portion of total demand is for residential heating, annual peaks can occur in evenings during the winter months, while peaks tend to occur in hotter climates late in the afternoon and evenings during the summer. Where gas is commonly used for space heating, water heating, and cooking, this also affects electricity load profiles. The ratio of industrial to commercial and residential loads also differs markedly from one place to another. These and other factors affect the shape of the seasonal daily load curve and the time of day and the time of year that system demand peaks.

The results of studies undertaken overseas on the impacts of EVs on electricity supply systems, while interesting, cannot be automatically applied to Western Australia. The large interconnected networks of North America and Europe have large numbers of users and generators, and energy can be traded between warm and cool regions and across time zones making for a relatively stable demand profile. According to the US Department of Energy (2010), by the end of 2008, total generating capacity in the US exceeded 1.1 million MW, and had net growth over the previous 12 months by 15,000 MW. In contrast, Western Australia's electricity system is small and isolated and total generation capacity is approximately 5000 MW (Independent Market Operator, 2009). For this reason, most of the analysis in this paper is based on local electricity load data, which is used to model the impacts of different charging behaviours of EVs on the Western Australian electricity transmission system, the South West Interconnected System (SWIS).

## 2. Overseas studies

At the time of writing, there has been no work published looking specifically at how EV loads will affect Australian electricity supply. Southern California Edison (SCE) has been studying the implications of electric vehicles for over a decade (Schirmer et al., 1996) to determine the primary challenges that large-scale EV adoption would create for the utility. The conclusion reached was that installed generation capacity was not a critical issue as SCE's supply system was capable of charging approximately 600,000 EVs using night-time charging before new generating capacity would need to be installed to meet the additional load created by electric vehicles. Other studies have also tended to confirm that installed generating capacity will not be a major constraint on electric vehicle take-up. The results of studies on the impacts of EVs on local grids, however, often come with caveats on when or how charging is undertaken. Lemoine and Kammen (2009), for example, found that electricity systems with sufficiently installed generation and transmission infrastructure to meet existing peak loads should (with a few caveats) be able to

handle charging scenarios that did not increase peak demand. They therefore concluded that in the case of the Californian electricity supply system, it was unlikely that the take-up of EVs would have potentially problematic impacts unless the number of vehicles exceeded 0.3 million and their charging patterns was completely unmanaged.

Many electricity utilities are keen that new markets for electricity to develop and have been quite bullish about possible EV take-up rates. A UK-based electricity and gas utility, E.ON, argued that if Plug-in Hybrid Electric Vehicles (PHEVs) accounted for 5–7% of total UK vehicle miles travelled by 2020, this would be equivalent to 7.5 TWh of electricity, which represented only 2.2% of current generating capacity and that the UK's networks would therefore cope (Hunt, 2008).

E.ON is aware, however, that EVs will have implications for planning new power plant as base-load nuclear power is not perceived to be sufficiently flexible and the output of wind farms is not perceived to be sufficiently predictable to be used to meet unpredictable EV recharging loads. This leaves thermal plant as the only option seen by E.ON as capable of meeting demand spikes when electric car owners plug in, in conjunction with using smart metering and tariff incentives to reduce the spikes (Hunt, 2008).

The study by Southern Californian Edison (Schirmer et al., 1996), however, also looked at the question of the capacity of its local grid infrastructure to cope with the increased demand that would be created by the adoption of EVs and concluded that electric vehicles present utilities with unique problems that utilities had not previously been required to consider. This was because electric vehicles:

- represent an entirely new type of non-linear load that cannot be characterised by examining any previous comparable load on the system;
- are mobile rather than stationary sources of demand;
- are charged for relatively long time periods and could therefore place significant coincident demand on the system;
- create loads that are unpredictable and that can appear on the system without advance notice and in multiple locations (Schirmer et al., 1996).

The study concluded that without proper planning and load management, substation and circuit rebuild costs could be substantial and that because of the random nature of EV purchasing and charging behaviour in particular, knowledge of charging behaviour that would result in EV loads was required in order to determine the location and consequences of the load impacts.

The study also concluded that the impact of multiple EV chargers on the electricity system could contribute to significant power quality problems not previously experienced by utilities on a large-scale, quoting one study that estimated that harmonic distortion levels could conceivably reach 90 percent at some locations given a large number of chargers connected to almost completely charged batteries during the night or early morning. Such a level of harmonic distortion could damage equipment, disrupt services, and reduce network efficiency.

Likely EV recharging behaviour has therefore been of key interest to utilities. Prior to the introduction of recharging infrastructure, a field study of nine converted Toyota Prius PHEVs was undertaken by the Idaho National Laboratory (INL) across five states in the USA in January and February 2008 (Morrow et al., 2008). One of the study's major findings was that over 80% of charging was undertaken at home between 6 pm and midnight (Fig. 1). This was considered most likely to be a consequence of limited recharging infrastructure available during the day as

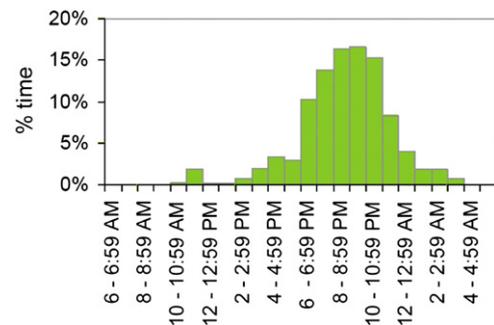


Fig. 1. Recharging behaviour found in Idaho National Laboratory (INL) Study (Morrow et al., 2008).

less than 20% of the trips resulted in a charge event. And as a consequence, the fuel savings achieved were small.

Although limited by the small number of vehicles in the trial, the results of these and other studies have raised concerns within utilities that are aware that consumer behaviour is not easy to manage, especially when the behaviour change benefits society as a whole rather than the individual. Electricity utilities have therefore realised that the way charging behaviour is managed from the outset, prior to the adoption of bad habits, will be a key issue and that realistic trials will need to be undertaken to establish what electric car users want (Hunt, 2008). Electric Power Research Institute (EPRI, 2010) has therefore proposed a new 3-year field study of Chevrolet VOLT PHEVs, financed in part by US utilities, and aimed at obtaining behavioural data for the purposes of capacity and network planning.

### 3. Simulation of the impacts of EV recharging on the Western Australian grid

Questions about the impacts that unmanaged EV charging will have on the Western Australian grid will remain until a reasonably sized field study is undertaken in WA. Given the lack of available data from field trials, we have instead simulated the most extreme charging scenarios to ascertain the effects on the overall transmission and generation capacity with the intention of finding the critical points. This was achieved by overlaying various vehicle charging scenarios over the half hourly electricity generation data, supplied by the local network operator, Western Power, for the period 1 July 2008–1 July 2009.

Three charging regime scenarios were used in the simulations. These were

- Scenario 1: Evening only recharging (16:00–23:00 h)
- Scenario 2: Night-time only charging (27:00–07:30 h)
- Scenario 3: Managed night-time charging using demand management functionality of smart metres

Two plausible recharging scenarios were not included in the simulations, a fast charging scenario, and daytime recharging based on recharging infrastructure, both of which would have significant impacts on the grid. Fast charging could increase the peak load, if a significant portion of electric vehicles was recharged simultaneously. Conversely fast charging could reduce the peak load by reducing the number of vehicles charging at any point in time. If recharging was sufficiently spread out over time, the first vehicles being recharged would have completed their recharge cycle prior to later vehicles plugging in.

Recharging based on public recharging infrastructure in car parks, etc., would allow a significant portion of the vehicle fleet to be recharged during day-time peak periods. A relatively small

number of electric vehicles recharged in this way could therefore have a significant impact on peak loads. Conversely, recharging infrastructure, by enabling daytime charging, will enable EV charging to be more spread out, and therefore relieve pressure in the peak, especially if the network operator was able to directly or indirectly manage demand. Any investment in recharging infrastructure would first require the widespread adoption of EVs.

Both of these scenarios were ignored because both would require specialised electricity supply infrastructure to be installed. This would require prior approval from the network operator to ensure that they did not cause local or system wide capacity constraints. In both cases, demand would be incorporated into the network and supply capacity planning processes, which would ensure that the supply system was not overloaded. They therefore do not need to be included in this analysis as the infrastructure investments would be planned and managed.

Both the number of vehicles being recharged and the rate of adoption are critical in determining whether the electricity supply industry will be caught out by new demand. Any such study is therefore highly sensitive to the accuracy of assumed adoption rates. With the uncertainty brought about by the global financial crisis, the estimation of EV adoption rates are largely guesswork based upon old data and as a result any study based upon these is of little use.

In order to eliminate the issue of take-up rates, the simulations undertaken in this study show the annual addition of EVs on the grid at the maximum possible rate of take-up. The maximum take-up rate (which would occur as a result of factors such as large increases in oil prices, oil supply shortage events, strong government incentives used to encourage the take-up of EVs, the adoption of inventive EV marketing and financing strategies) was taken to be the maximum number of new vehicles purchased in Western Australia over recent years. During the last economic boom period, the highest number of new vehicles sold in Western Australia in any one year was 91,288 in 2007. The worst case scenario (as far as a sudden loading on the grid is concerned) therefore assumes a maximum rate at which the WA vehicle fleet could be converted to electric vehicles in any one year, taken to be 90,000, vehicles per year. Factors such as population growth and increased economic activity impact on the demand for both vehicles and electrical power. Assumed new vehicle sales are held static at 90,000 vehicles throughout the simulation period because EV demand is reference to the current size of the electricity market.

As there are currently approximately 1.8 million passenger vehicles licensed in Western Australia, each 90,000 increment therefore represents a turnover of approximately 5% of the total vehicle fleet. Ignoring lifetime issues, this would mean that the entire Western Australian vehicle fleet would be converted to EVs over a 20-year period at this aggressive take-up rate. The tenth increment then represents a scenario where 50% of the fleet has been replaced by EVs over 10 years.

The simulations assume that electric vehicles are recharged from home using the standard 10 A home electricity supply and that each vehicle being recharged represents a 1.5 kW load and that each vehicle is recharged for 4 h periods, which would be sufficient to recharge the batteries of EVs driven 40 km, the average daily distance travelled by a vehicle in Western Australia.

The simulation models the impact of electric vehicle recharging, on the actual load data (Western Power, 2009) in the period 1 July 2008–1 July 2009. The focus is then turned to the change in load on the day of maximum peak in order to judge the affect on the annual peak, the load duration curve which is a standard representation of generating and network utilisation, and the effects on utilisation of the different levels of generation.

### 3.1. Scenario 1: Evening only recharging (16:00–23:00 h)

The assumed percentage of electric vehicles that start to be recharged in any one half-hour interval is shown in Fig. 2. Using the above assumptions of a 4 h recharging duration for each vehicle, this would result in the total percentage of electric vehicles being recharged in any one half-hour period as shown in Fig. 3.

The impact that this charging regime would have on the peak load on the maximum peak load day was modelled over 10 years, at the maximum possible take-up rate and the results are shown in Fig. 4. The lowest (thick blue) line represents the existing load curve. The simulation indicates that under an unmanaged evening recharging scenario, the recharging of EVs does not result in the maximum peak load being exceeded until the number of electric vehicles exceeds approximately 180,000 vehicles, or 2 years at the maximum possible take-up rate (red line, third from the bottom).

The system capacity utilisation curves under Scenario 1 (Figs. 5 and 6) indicate that as the number of electric vehicles is increased, both the peak load and the level of utilisation of peak load capacity (generation and network capacity) increase quickly, while the capacity required to meet base-load remains relatively unchanged.

Under this scenario, the electricity system would initially become more efficient as it would result in increased utilisation of the existing peak supply capacity. However, once the number of electric vehicles in the WA fleet exceeds approximately 180,000, this benefit is reduced as further investment in

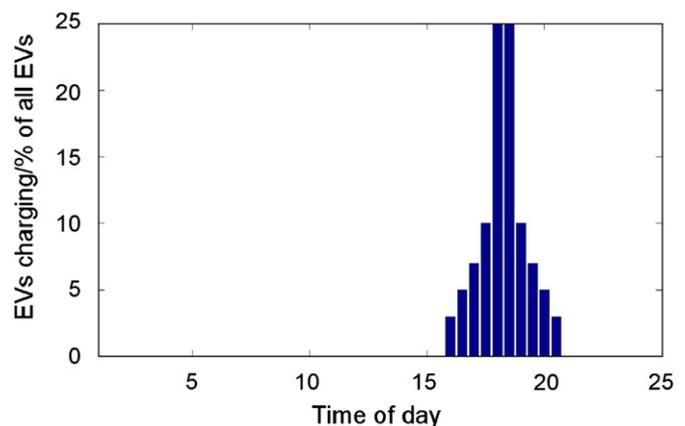


Fig. 2. Percent of electric vehicles that start a recharge cycle in each half-hour interval (Scenario 1).

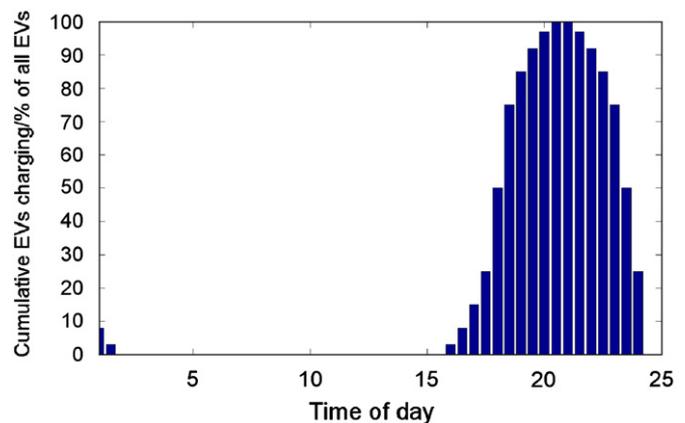


Fig. 3. Cumulative percent of electric vehicles being recharged in each half-hour interval (Scenario 1).

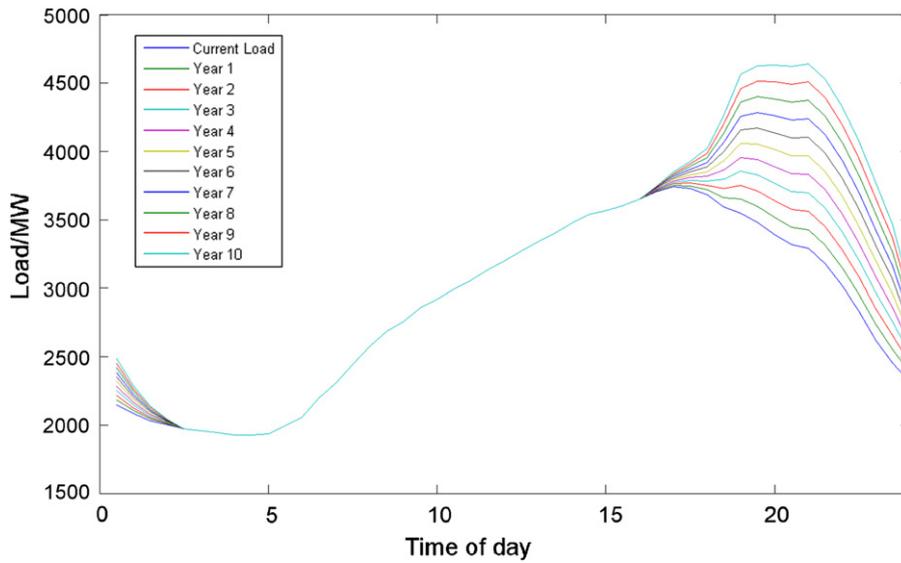


Fig. 4. Impact of recharging on the peak load on maximum peak load day (Scenario 1). (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

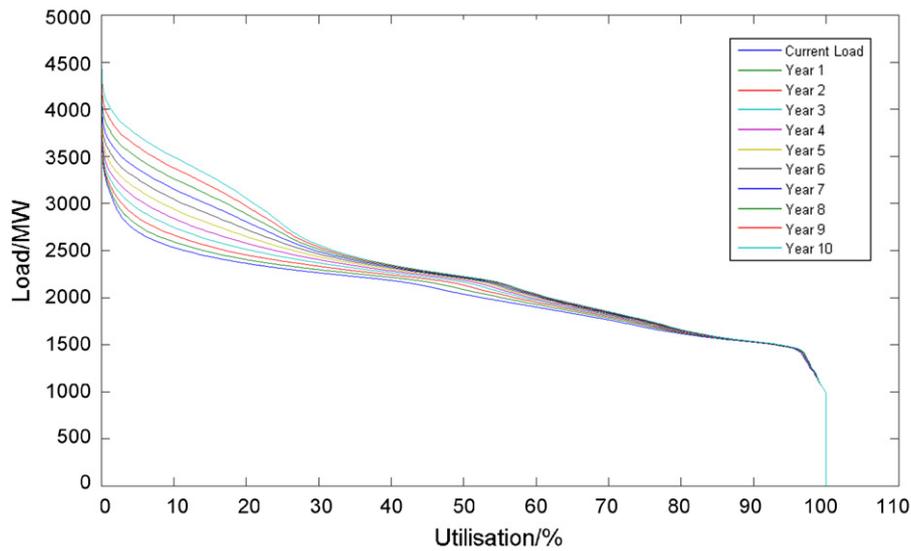


Fig. 5. Effect on load duration (Scenario 1).

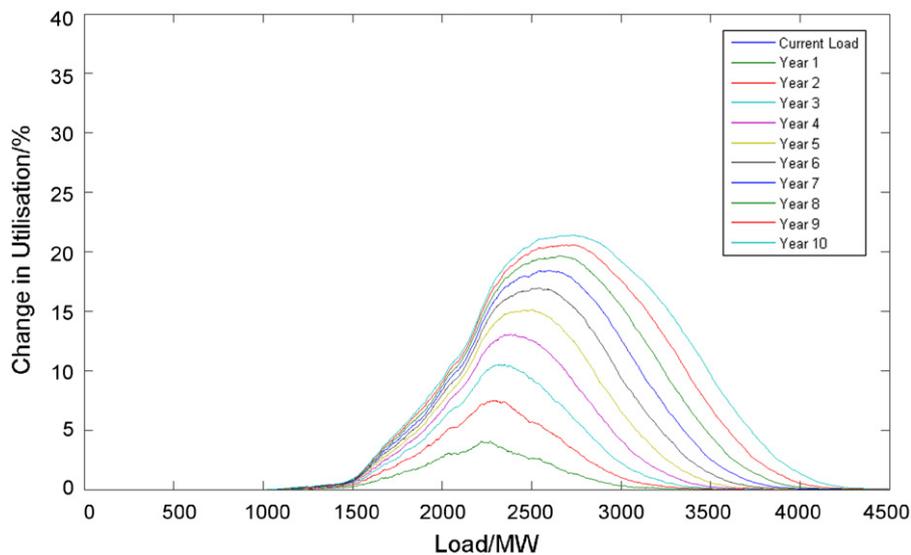


Fig. 6. Change in utilisation of infrastructure (Scenario 1).

additional peaking capacity is required. As peaking plant is utilised for a relatively small proportion of the time, this recharging regime would result in the electricity supply industry becoming less efficient once that threshold number of vehicles

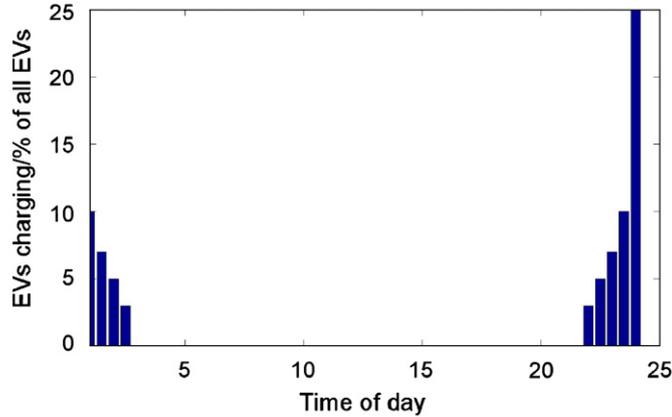


Fig. 7. Percent of electric vehicles that start a recharge cycle in each half-hour interval (Scenario 2).

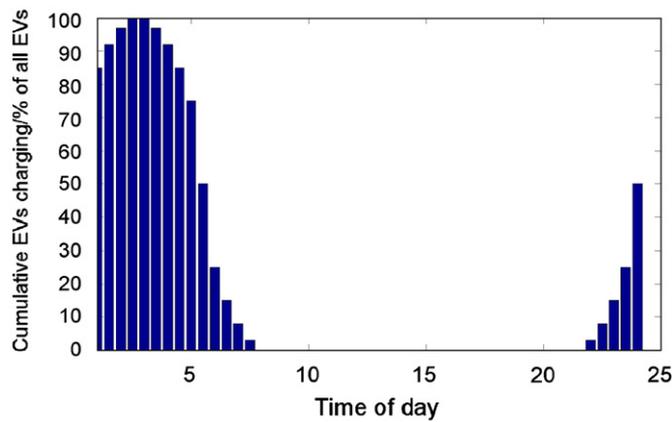


Fig. 8. Percent of electric vehicles that start a recharge cycle in each half-hour interval (Scenario 2).

was reached. This would raise questions over the social equity of flat rate electricity tariffs as it would increase further the subsidisation of peak usage by off-peak usage.

At the maximum take-up rate vehicle charging under Scenario 1 would increase the annual maximum peak demand after 2 years.

It would require an extreme summer heatwave event, coincident with a highly unlikely sudden and rapid addition of over 180,000 electric vehicles, combined with all electric vehicle owners recharging their vehicles during the evening for the capacity of the WA electricity supply system to be exceeded under this evening-only recharging scenario. Based upon the experience gained from the sales of first generation hybrid electric vehicles, which totalled 1345 vehicles in Western Australia by the end of 2008 (Federal Chamber of Automotive Industries, 2009), it will be many years before electric vehicle penetration reaches these levels.

### 3.2. Scenario 2: Night-time only charging (22:00–07:30 h)

The assumed percentage of electric vehicles that start to be recharged in any one half-hour interval under this scenario is as shown in Fig. 7 and the cumulative proportion of electric vehicles being recharged in any one half-hour period is shown in Fig. 8.

The impact that this recharging regime would have on the peak load is shown in Fig. 9. The simulation indicates that under this recharging scenario, the charging of electric vehicles would not result in the maximum peak being exceeded until the number of electric vehicles in the WA vehicle fleet exceeded well over 900,000 vehicles.

The system load and capacity utilisation curves (Figs. 10 and 11) show that even relatively low numbers of vehicles recharging under this recharging regime have an impact upon the night-time demand trough and increase the utilisation of base-load generating capacity.

As base-load tends to be met using lower cost high efficiency thermal generation plant, filling in the night-time demand trough will increase the utilisation of this capacity, making the electricity supply system more economically efficient and more equitable under the current market regime.

This approach may lead to sudden spikes in demand on the minute/half hour/hour as vehicle owners set their vehicles to start charging at a specific point in the evening. This could be further magnified if an off-peak/low cost rate is published.

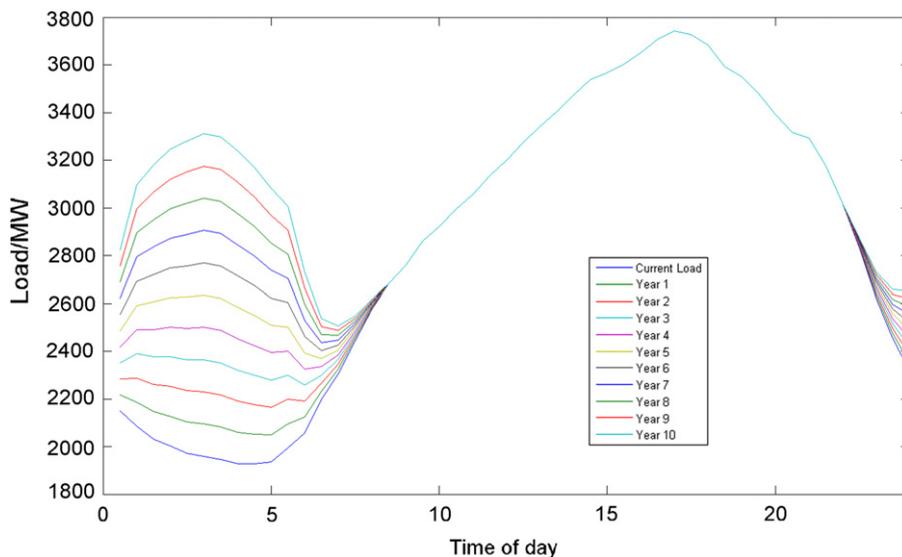


Fig. 9. Impact of recharging on the peak load (Scenario 2).

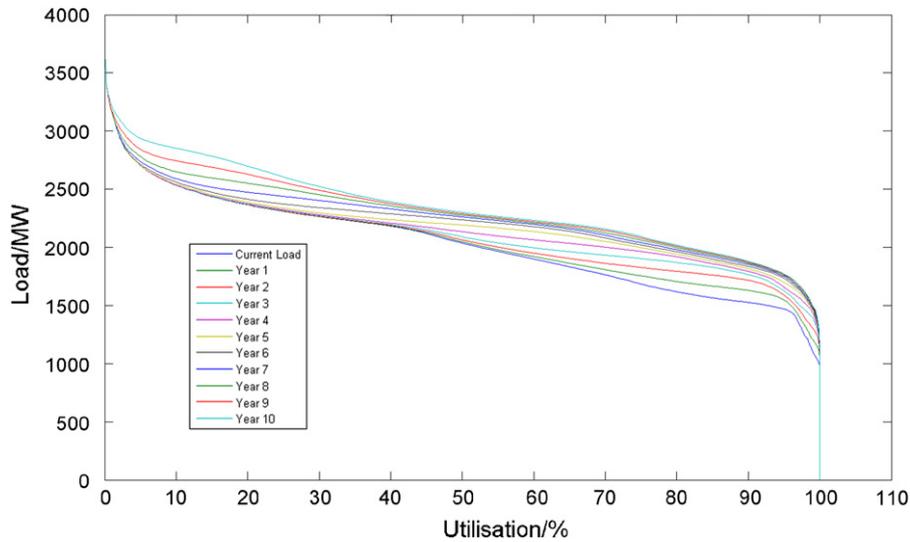


Fig. 10. Effects on load duration (Scenario 2).

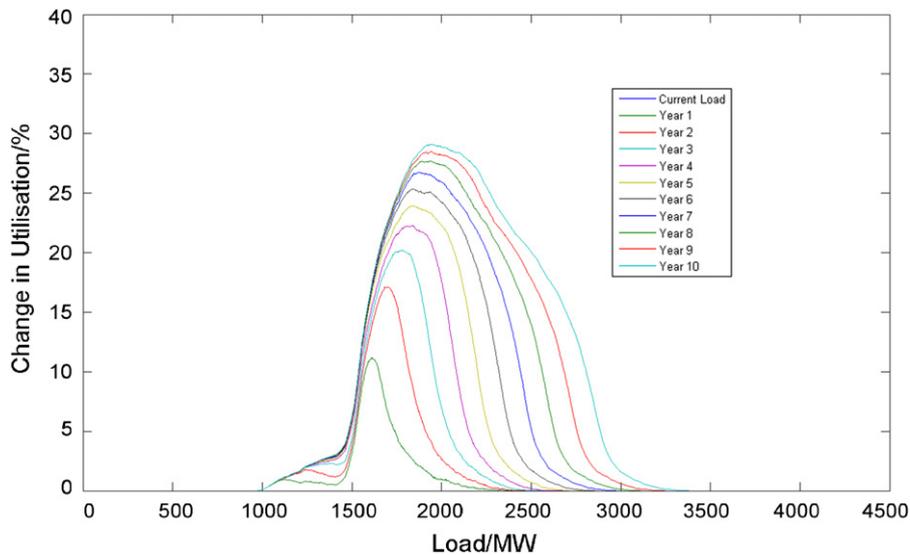


Fig. 11. Change in utilisation of infrastructure (Scenario 2).

3.3. Scenario 3: Managed night-time charging using demand management function of smart meters

Under this scenario it was assumed that recharging is managed remotely by the network operator, via a smart metre, to ensure that less than 90% of vehicles are being recharged at any one time and to shape demand due to EV recharging to maximise the benefits of off-peak charging.

The assumed percentage of electric vehicles that start to be recharged in any one half-hour interval under this scenario is as shown in Fig. 12 and the corresponding cumulative percentage of electric vehicles being recharged in any one half-hour period is shown in Fig. 13.

The impact that this managed night-time recharging regime would have on the peak load is shown in Fig. 14. The simulation indicates that under this recharging scenario, the night-time peak remains lower than under Scenario 2 and well under the maximum daytime peak.

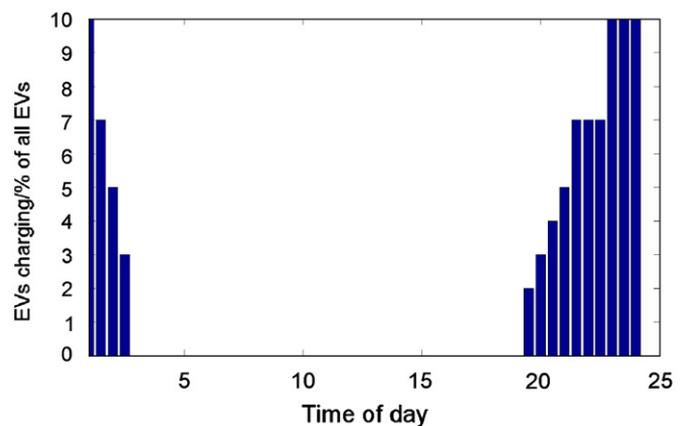


Fig. 12. Percent of electric vehicles that start a recharge cycle in each half-hour interval (Scenario 3).

The system capacity utilisation curves (Figs. 15 and 16) show that, as with Scenario 2, vehicle recharging under this recharging regime begins to fill the night-time demand trough

and that the utilisation of the system increases with the number of vehicles.

### 3.4. Analysis

A closer examination of the system utilisation curve under Scenario 2 (Fig. 10), and to a lesser degree under Scenario 3 (Fig. 15), shows that while none of the 10 increments in the numbers of electric vehicles affects the height of the peak, from approximately the sixth increment (540,000 vehicles) the slope of the curve increases as the number of vehicles is increased. This indicates that increased vehicle numbers begin to have a greater impact on peak demand and a lower impact on base-load demand utilisation. This effect is more obvious in the change in utilisation curves (Figs. 11 and 16). Under Scenario 2, the peak of the curve becomes noticeably wider on the third increment (270,000 vehicles) and then begins to extend outwards on the fourth increment (360,000 vehicles). The effect is less obvious until the fifth increment Scenario 3 (450,000 vehicles). This indicates that although the benefit of night-time charging is significant (Scenario 2) and could be marginally improved by coordinating vehicle charging (Scenario 3), there is actually a limit to the benefit that night-time

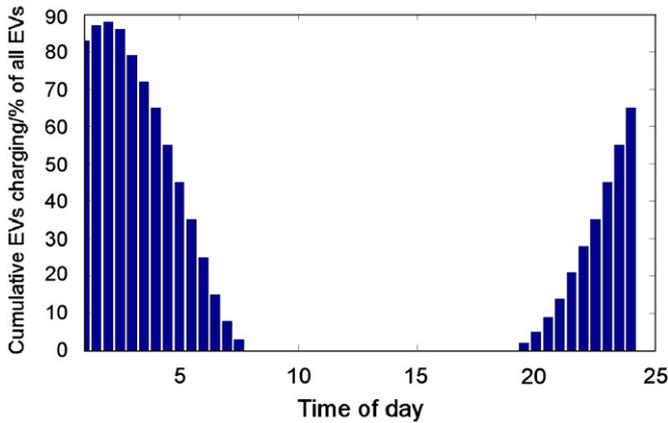


Fig. 13. Cumulative percent of electric vehicles being recharged in each half-hour interval (Scenario 3).

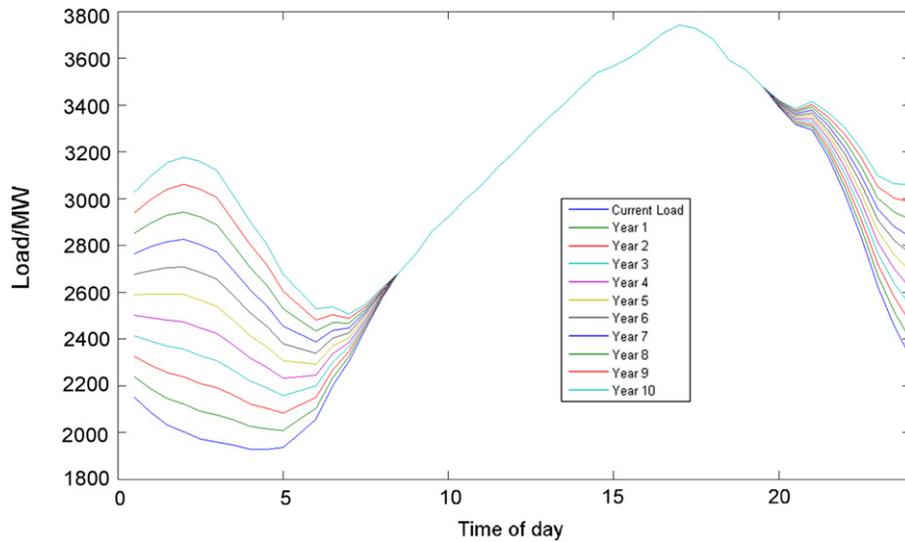


Fig. 14. Impact of recharging on the peak load (Scenario 3).

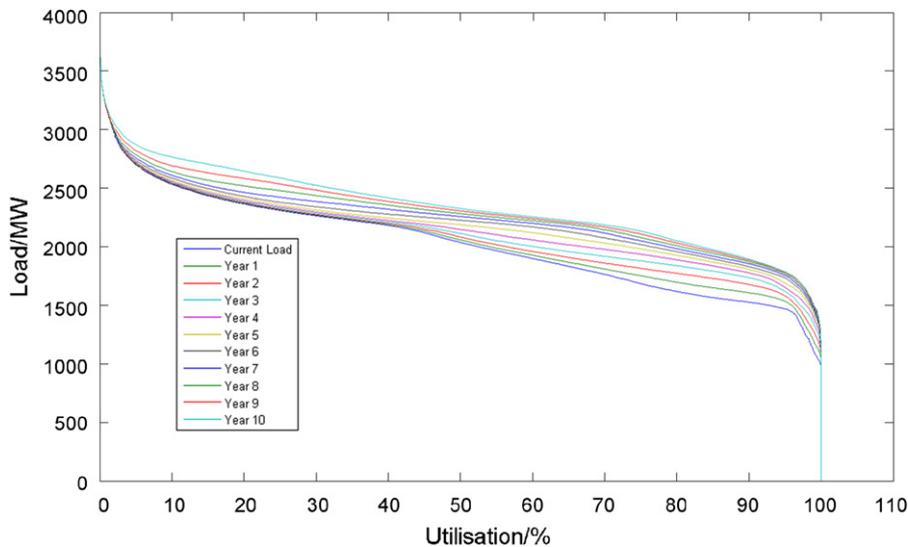


Fig. 15. Effects on load duration (Scenario 3).

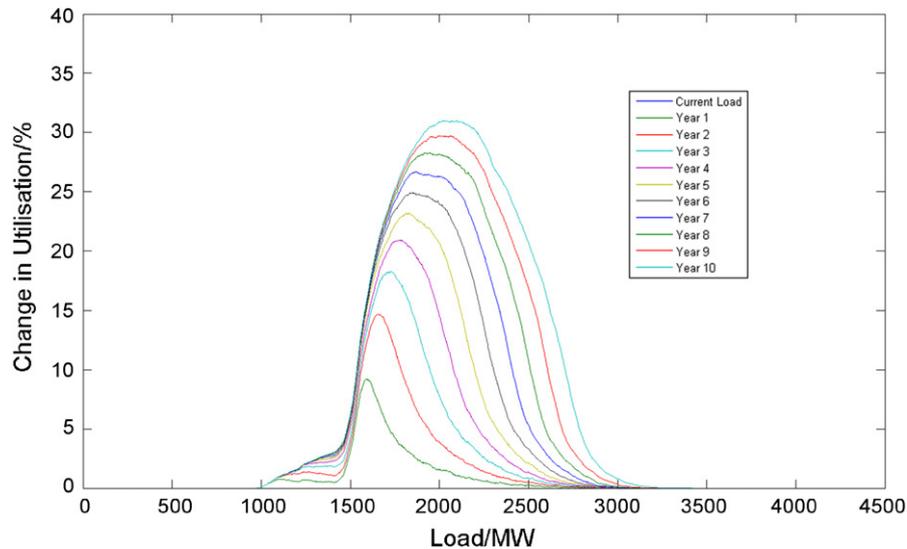


Fig. 16. Change in utilisation of infrastructure (Scenario 3).

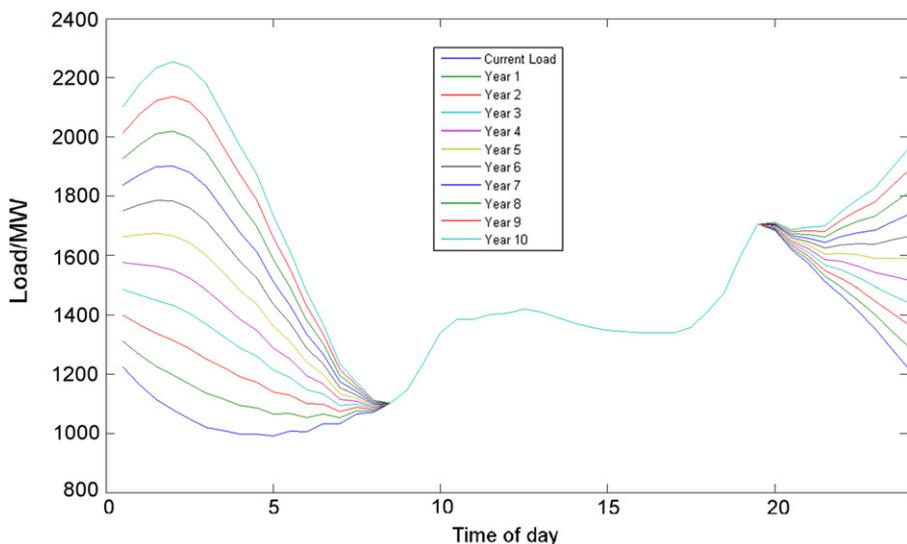


Fig. 17. The impact of recharging under Scenario 3 on the lowest peak demand day.

recharging can have as the average night-time trough over the year is filled and then “overflows” when EVs make up approximately 15% of the vehicle fleet. At that point, a night-time peak begins to emerge that does not benefit cheaper base-load generation and begins to increase the average unit cost of supply.

The simulation suggests that the Western Australian electricity supply system could also accommodate a significant amount of daytime recharging in conjunction with night-time recharging regimes. On all but a handful of days each year electricity demand is significantly lower than the summer peak load, and as a result there is significant spare capacity available through the year. This is illustrated well by the simulated impacts of recharging under Scenario 3 on the day with the lowest daytime peak (Fig. 17), which occurred on 24 April 2009. While the benefits of night-time charging are clear, utilisation of base-load generating capacity can be increased further by encouraging a degree of daytime charging except during the most extreme summer peak days. This may or may not be practical.

The simulation under Scenario 3 indicates that incremental gains could be achieved by managing or coordinating vehicle charging to spread load over the entire night-time period. However, the gains would not be significant until EV numbers made up a significant

proportion of the total WA vehicle fleet and investment in smart meters would be required under this scenario. Persuading vehicle owners to accept direct control of recharging by the network operator may also require some form of incentive. The economic benefits gained from the marginal improvements in system utilisation would need to be weighed against the incremental economic costs of having to offer incentives to vehicle owners together with the capital investment in any enabling infrastructure and systems. These costs are likely to outweigh the benefits until electric vehicles make up between 80% and 90% of the total WA vehicle market when EV charging would dwarf other loads and the peak demand would occur at night.

#### 4. Impacts of EV recharging on the distribution system

The simulations above show the possible impacts of electric vehicle recharging under various scenarios at the generation and transmission level. At the local distribution level, demand for EVs is likely to be demographically (and therefore geographically) clustered, particularly during the early periods of market development. Low market penetration levels of EVs at the state level could still

correspond to a high penetration levels in specific suburbs. Southern Californian Edison (Schirmer et al., 1996) noted in its study that while the generation and transmission infrastructure could support the new demand created by electric vehicles, the use of even a single charger could potentially double a household's electrical demand and the widespread adoption of EVs within its service area could produce significant impacts on its localised distribution systems. By assuming Tobler's Law of auto-spatial correlation, the authors of the SCE report concluded that it was reasonable to assume that EV ownership would be spatially clustered and that this would put a disproportionate burden on some localised substations and feeders (Schirmer et al., 1996).

A more recent modelling study commissioned by Duke Energy (Mosheni and Stevie, 2009), however, used statistical procedures to model the likely spatial uptake of electric vehicles in a number of cities in the USA and then used this model to run load simulations. Repeated runs of the simulation indicated that local transformers were overloaded in only a relatively small number of incidences.

It is, however, more likely that a one in 10 summer peak event combined with high take-up rates of EVs in particular areas could cause localised problems. The fact that EVs represent a mobile load, if daytime charging facilities are available, makes modelling of their impact on the grid difficult. While it can be established in advance the likely suburbs in which EVs might be clustered at night by undertaking market research or constructing models based upon socio-economic data, it may be more difficult to predict where EVs might cluster during the day and to what extent. If EVs are designed and marketed to meet a specific need, a particular take-up of EVs dispersed through the metropolitan area may result in a disproportionate number of EVs parked in a particular area during the day. For example, if EVs are market towards the commuter, city car parks might have a relatively high proportion of EVs. This would be further compounded if the quality and number of charging facilities varied from car park to car park. A feeder supplying power to that car park might then have a correspondingly disproportionate increase in power demand in the hours immediately after the morning rush hour. In addition to demand pressures, the clustering of rectifiers in a car park would introduce serious power quality issues with the introduction of harmonics into the local network.

However, even these issues should be manageable as upgrading distribution capacity is relatively rapid to implement in comparison to the time it takes to increase generation capacity. This is demonstrated by the fact that in Western Australia, the network operator, Western Power, has managed to upgrade local distribution systems to meet the increased loads created by the widespread adoption of air-conditioning. In addition, the metropolitan network in the Perth area has coped well with the affects of population growth, namely the need to increase residential density. Land in suburban areas has been rezoned and developed such that individual blocks holding a single dwelling with no air-conditioning now contains a number of houses, each with one or more air-conditioning units. In addition, urban sprawl has resulted in the creation of new suburbs.

## 5. Summary

The simulation undertaken in this study indicates that if managed well, even a rapid take-up of electric vehicles would not create significant problems for the WA electricity supply system. On the contrary, the take-up of EVs appears far more likely to present financial opportunity for the electricity supply industry than a looming disaster as it has the capacity to allow vast improvements in infrastructure utilisation. By shifting loads

to night-time periods, the electricity supply system in Western Australia would be made more efficient as base-load utilisation would be increased and the need for new peak load capacity avoided until the numbers of vehicles reached well over 900,000. Electric vehicle recharging would therefore provide a new source of income to the electricity supply industry without the requirement of additional capital investment for many years, making the industry significantly more profitable. This could reduce tariffs or provide a funding source to support investment in renewable energy generation or carbon capture and storage schemes.

There would be a limit on the extent to which shifting load to night-time periods would benefit the system as electricity network companies tend to overload transformers during peak load days and rely on night-time cooling demand period at night to allow the transformers to cool. The capacity to do so would be decreased as night-time load is increased.

From the results of the simulation exercise it is clear that the way that demand is managed will have significant implications for the profitability of the electricity supply industry. Simply encouraging night-time charging via, for example, an appropriate tariff structure would bring about most of the benefits offered by night-time recharging.

There are some incremental gains to be made by coordinating vehicle charging as per Scenario 3, to spread load over the entire night-time period. However, these are not significant until EV numbers significantly dominate the vehicle fleet and it would require some infrastructure investment to implement such a scheme. In addition, convincing vehicle owners to allow system management to directly manage the charging of their vehicle may not be easy and might require a further financial incentive. As such, if the marginally better utilisation of capital is the only gain, the costs will probably outweigh the benefits until EV numbers reach in the region of 80–90% of the market when EV charging dwarfs other loads and the peak demand occurs at night. Larger gains would be likely to be achieved by encouraging a managed daytime charging regime with the roll out of managed recharging infrastructure.

It is simplistic to only look at the overall demand profile and introduce policies to fill valleys and plateau the peaks without considering the network. This approach assumes uniform demand across the entire network and therefore does not reflect the ebb and flow of demand with the daily movements of the general population. The distribution component of the network reticulates power to the many end users, being homes, hospitals, businesses, and infrastructure such as rail from substations via local feeder circuits. Each component of the network (lines and transformers) has its own unique mix of customers and is loaded to its own unique proportion of its rated loading.

Investigation of how EV demand will affect the various component parts of the network is therefore a major project in itself and perhaps one for the network operator. In advance of that, local field studies are needed to establish charging behaviours and how effective different incentive regimes, such as off-peak rates, together with the availability of daytime charging infrastructure are in managing demand.

## Acknowledgements

The authors would like to thank Western Power for the supply of grid data and CREST for the funding of the project.

## References

- Book, M., Mosquet, Z., Rizoulis, D., Sticher, G., 2009. The Come Back of the Electric Car? How Real, How Soon, and What Must Happen Next. The Boston Consulting Group Report, Boston, USA.

- CO2Smart, 2010. WA EV Trial. (Online) Available at: <http://www.co2smart.com.au/projects/ev/> (accessed 22 October 2010).
- Cunningham, J.S., 2009. An analysis of battery electric vehicle production projections. B. Mech. Eng. Thesis. Massachusetts Institute of Technology, Boston, MA.
- EPRI, 2010. GM Vehicle Demonstrations. Project Proposal/Marketing. EPRI EPRI, Palo Alto.
- ETSA Utilities, 2008. Air conditioner "Beat the Peak" trial to expand following solid results over two years. Media Release. ETSA Utilities, Keswick, South Australia.
- Federal Chamber of Automotive Industries, 2009. Sales by Fuel Type 2001 to 2008 and YTD Mar 2009 Prep Apr09. Federal Chamber of Automotive Industries, Canberra, ACT.
- George Winkelfeld and Associates, 2004. A national demand management strategy for small air-conditioners. The National Appliance and Equipment Energy Efficiency Committee and The Australian Greenhouse Office, Canberra, ACT.
- Graham, P., Reedman, L. & Poldy, F., 2008. Modelling of the Future of Transport Fuels in Australia: A Report to the Future Fuels Forum. (Online) CSIRO (Energy Transformed Flagship Report IR 1046) Available at: <http://www.csiro.au/resources/Fuel-For-Thought-Modelling.html>.
- Hodson, N. & Newman, J., November 2009. A new segmentation for electric vehicles. McKinsey Quarterly Automotive and Assembly Practice, Available at: <http://www.cars21.com/files/news/nese09.pdf>.
- Hunt, J., 2008. A move to electric vehicles could increase the strain on the UK's power infrastructure. (Online) Utility Week Available at: <http://www.utilityweek.co.uk/features/uk/a-move-to-electric-vehicles-co.php> (accessed 2009).
- Independent Market Operator, 2009. Reserve Capacity Mechanism Review Report. (Online) Independent Market Operator. Available at: [http://www.imowa.com.au/f875,52032/RCM\\_ReportV5\\_PUBLISHED\\_1\\_.pdf](http://www.imowa.com.au/f875,52032/RCM_ReportV5_PUBLISHED_1_.pdf).
- Lache, R., Galves, D., Nola, P., 2008. Electric Cars: Plugged In. Auto Manufacturing, 9 June.
- Lemoine, D.M. & Kammen, D.M., 2009. DRAFT-Economic Assessment of All-Electric Vehicles. (Online) Available at: [http://www.tsrc.berkeley.edu/research/DRAFTLemoine\\_Kammen\\_EV-2009-02-06b.pdf](http://www.tsrc.berkeley.edu/research/DRAFTLemoine_Kammen_EV-2009-02-06b.pdf) (accessed 2010).
- Marfisi, E.P., Upton, C.W., Agnew, C.E., 1978. The Impact of Electric Passenger Automobile on Utility System Loads 1985–2000. EPRI MATHTEC Inc Princeton, NJ.
- Morrow, K., Karner, D., Francfort, J., 2008. Plug-in Hybrid Electric Vehicle Charging Infrastructure Review. U.S. Department of Energy Idaho National Laboratory, Washington, DC.
- Mosheni, P. & Stevie, R., 2009. Electric vehicles: holy grail or fools gold? Paper presented to the IEEE Power and Energy Society 2009 General Meeting, 26–30 July. Calgary, Canada.
- National Research Council of the National Academies, 2009. Transition to Alternative Transportation Technologies—Plug In Hybrid Electric Vehicles. Washington, D.C.: The National Academies Press.
- Office of Energy, 2004. The impact of residential air-conditioning on the Western Australian Electricity system. Information Paper. Office of Energy Government of Western Australia, Perth, Western Australia.
- Schirmer, D., Morales, E.T., Boruah, H., 1996. On The Integration of GIS within an Electric Vehicle Program for Predictive Analysis. (Online) Available at: <http://proceedings.esri.com/library/userconf/proc96/to450/pap423/p423.htm> (accessed 2010).
- The REV Project, 2010. The REV Project. (Online) Available at: <http://theREVproject.com> (accessed 12 October 2010).
- US Department of Energy, 2010. Existing Capacity by Energy Source. (Online) Department of Energy Available at: <http://www.eia.doe.gov/cneaf/electricity/epa/epat1p2.html> (accessed 11 August 2010).
- Western Power, 2009. Half Hourly Demand Data. Private Correspondence. Western Power, Perth Western, Australia.