Energy Usage Patterns for Driving and Charging of Electric Vehicles

by

Stuart Speidel

BEng

THE UNIVERSITY OF
WESTERN AUSTRALIA

This thesis is presented for the degree of
Doctor of Philosophy
of
The University of Western Australia

School of Electrical, Electronic and Computer Engineering

June 2019

Abstract

Electric vehicles (EVs) are currently a feasible and attractive alternative to their internal combustion engine counterparts. Electric vehicles require access to compatible charging infrastructure, which needs to be safe, secure and available. The stations need to be monitored, have car bays available, be in convenient locations, be spread-out appropriately, be in areas where enough power is available, and many more other considerations. There are different configurations of stations, which provide various power outputs, use different connector types, different communication protocols, and there are many different international standards. These stations are mostly grid connected, which will create additional loads that need to be considered by electricity providers. Also, the electricity generated from non-renewable resources negates some of the environmental benefits of electric vehicles, and the intermittent nature of certain renewables needs to be optimised with smart charging solutions.

In this thesis, the results of several trials are discussed. As a part of the Western Australian Electric Vehicle Trial, 13 ICE vehicles were converted from petrol to electric, and 23 charging outlets were installed throughout Western Australia, with usage data recorded over their lifetime. Solar energy data collected at several installations was used in conjunction with energy storage systems to measure the renewables' impact on charging, including data collected from buildings to consider regular household power usage. The REView portal was created for users to monitor their behaviour, which includes charging stations, vehicles tracking, renewables usage along with billing. Finally, a fast charging station was installed and monitored at UWA, and its data combined with the data collected from previously installed Level-2 AC charging stations in the Perth metro area.

Combining all this information, this thesis gives an insight into electric vehicle technology, driving/ usage/ charging patterns of EVs, as well as renewable energy and EV charging infrastructure.

Table of Contents

Acknowledgements

Special thanks to Professor Thomas Bräunl for supervising me throughout the PhD research project, and Emeritus Professor John Taplin and Adj. Professor David Harries in co-supervising the research.

I would also like to extend my sincere thanks to the following people for their hard work and help throughout the project

Fakhra Jabeen
Doina Olaru
Brett Smith
Ian Hooper
Rob Mason and all of EV-Works
Kai Li Lim

Stuart Speidel

December 2018

Introduction

Climate change represents a real and growing threat to our lives today and in the future. Increasing global temperatures changes the environment we live in, threatening places, species and people's livelihoods. In response to this, Australia, along with 195 other countries adopted the Paris Agreement, aiming to limit the global average temperature increase to 1.5 degrees Celsius, achieved by each member country reducing their amount of carbon emissions. The statistic measuring the amount of atmospheric carbon dioxide is described as the "Single Most Important Stat on the Planet" by environmentalists, with levels reaching a record high in May 2019 [1].

There are many different contributors of carbon emissions in Australia, of which the transportation sector contributed 17.8% in 2017. The transport sector generates carbon emissions from their reliance on Internal Combustion Engine (ICE) vehicles which also produce other pollutants. From 1990 to 2017 this carbon emission sector grew by 60.8% the main drivers of which was the continuing growth in the number of passenger vehicles [2]. Transportation is fundamental to the function of our society, and as the number of vehicles in Australia continues to grow, alternative forms to ICE vehicles have been widely investigated. For the purpose of this research, Electric Vehicle (EV) have been identified as a feasible alternative to ICE vehicles, in line with the overall aim of reducing carbon emissions.

When this research started in 2011, EVs went from being unavailable in the consumer market by original equipment manufacturers (OEM). Today, many hybrid and fully electric models are available for purchase from several OEMs. In 2017, the International Energy Agency noted an increase of 56 percent globally from electric vehicle sales [3]. EV sales in Australia increased 67 percent from 2016 to 2017 [4], however that increase only represents a very small number overall being purchased only making up 0.2 percent of the vehicle sales market in 2017 [5]. By comparison, Norway one of the world's strongest adopters of EVs, had an EV market share of an impressive 58.4 percent in 2018 [6].

Internationally, the uptake of EVs is far greater than in Australia. Germany subsidises consumers €4,000 (~ AUD$6,500) [7] for the purchase of an EV, California in the United States is offering up to US$10,000 US (~ AUD$14,000) with state rebates and federal tax credits [8], and Norway offers scores of incentives including reduced and removed taxes, removed fees and allowances for drivers to use bus lanes [9]. Australia offers no direct incentives for purchasing an EV, and arguably a financial disincentive in the form of a luxury car tax, which is a major factor in their slow uptake.

Despite the slow uptake, electric vehicles are becoming more mainstream in Australia. As Electric Vehicles are introduced, they introduce several new engineering challenges including the energy generation, charging infrastructure, environmental policies and standardisation. In order to better understand the effects EVs will have in Western Australia, and all of Australia, several trials were performed with the support of Western Australian universities, government agencies, councils and private businesses. These looked at many different aspects of EVs, from driving behaviours, purchasing uptake, charging stations, standards, electricity generation and transmission and the impact of electric vehicles on the electricity grid.

Consumer usage

We wanted to investigate how West Australian consumers and various industries would use EVs in comparison to an ICE vehicle. Questions such as driving behaviour, distance travelled and charging - how they charged, where they charged and how much energy they were using while charging.

Charging Infrastructure

As electric vehicles are introduced, they require access to compatible charging infrastructure, which needs to be safe, secure and readily available. As part of the research, analysis of what charging infrastructure would be used, depending on behaviour and charging requirements was examined. Due to the range restrictions of EV batteries, we examined the installation of public charging infrastructure to assist consumers with recharging. Public charging infrastructure was available in several different levels, with level 1 charging infrastructure being the equivalent of household sockets, level 2 charging infrastructure offering three times the energy as level 1, and level 3 charging infrastructure being the fastest and the highest energy input. Due to the variation in the level of charging speeds between level 1, level 2 and level 3 charging stations, research was conducted into driver behaviour and station usage.

What impact EVs have on the electricity grid was also explored. In Western Australia, the power grid is managed by Western Power. They must predict market electricity fluctuations to maintain the stability of the grid with its growing demand, while reducing costs. New technologies with high energy demand can upset their ability to predict, leading to expensive infrastructure improvements to support the increased load on the grid. The charging of EVs has this potential to increase the demand on the electricity grid. The research aimed to analyse the charging behaviour and potential impact of this increase.

Interconnectivity

Public and private charging infrastructure have the potential to be monitored and automatically reported on. This gives insight into usage patterns that can direct the deployment of further infrastructure. Throughout the trials, the charging infrastructure installed contained devices that automatically delivered live data for analysis, and through this research we will examine the valuable insights such interconnectivity can provide.

Renewable Energy

In Australia, the majority of electricity produced comes from coal power stations. When charging from electricity generated by coal, the EVs carbon emissions are similar to modern highly efficient combustion vehicles. To produce emission free transportation, the EVs would need to be charged from renewable energy sources such as solar, wind, hydroelectricity and geothermal. Some types of renewable energy also introduce its own problems, with solar only being available on clear sunny days, and wind power being intermittent, leading to new solutions such as energy storage.

The research examined how renewable energy can support EVs, and how the potential limitations of renewable energy sources could impact on charging.

The trials performed

The Western Australian Electric Vehicle Trial (2010 – 2012)

This Western Australian Electric Vehicle Trial aimed to assess the suitability of EVs as a replacement for ICE vehicles in several different businesses and councils around Western Australia, including:

- University of Western Australia
- RAC
- Water Corporation
- Department of Transport
- Department of Environment and Conservation

- Telstra
- City of Mandurah
- City of Perth
- City of Swan
- The West Australian
- Mainroads
- Landcorp.

The trial was managed by CO2 Smart. At the time there were no available electric vehicles from automotive manufacturers. As such, the company EVWorks converted 11 Ford Focus ICE vehicles to electric vehicles, and with two UWA electric vehicles, in total 13 EVs around Western Australia had data loggers installed in them that monitored battery state, headlights, air-conditioning and heating, charging, and ignition statuses, battery level, GPS position, speed and more.

The vehicles were used in their day to day activities by the participating partners over two years, and the data collected generated insights into driver behaviour and EV usage including charging and energy usage that is used throughout this research.

The WA Charging Station Trial (2010 – current)

Twenty-three Electromotive EV charging stations for the WA Charging Station Trial were installed, modified and the communications protocols reverse engineered to stream data. This information was combined with the EV data loggers to create a complete picture of the EV usage.

The data is available to users through a billing system and provides live status updates. The stations allowed us to test consumers using the new technology and standards and examine the challenges of installing the stations.

UWA Future Farm, UWA Human Movement and Energy Made Clean (EMC) Solar installations and German Wind Farm (2010 – current)

Solar logging systems from UWA, UWA Future Farm and Energy Made Clean (EMC) were made available for data collection. This information was used to show the potential for direct offsetting of energy usage and indirect grid feedback energy offsetting. Wind energy was also considered with energy information from a German wind farm as baseline data.

Building energy use data was collected from the UWA “Human Movement” building to show the overall energy use of a large corporate building. This data was used to show the potential of completely offsetting all energy usage for a building with renewable energy and the potential for grid energy storage.

UWA DC Charging Station (2014 – current)

In November 2014 a 50 kW Veefil fast DC charging station was installed at The University Club of Western Australia. It was the first fast charging station installed in Western Australia and can charge a compatible electric vehicle to 80% state of charge in 20 minutes.

The station was installed to test how electric vehicle owners would utilise a fast charging station and was made available for free use. The data from the station was collected for the duration of the trial, including user information, time of use, energy usage, and connection time.

RAC Electric Highway (2016 – current)

The RAC installed an ‘Electric Highway’ consisting of 11 DC fast charging stations across Western Australia to support their sustainable mobility agenda. The stations where placed at locations from Perth to Augusta, spanning over 300 kilometres, to extend the usability range of EVs.

Data collected from the stations was used in conjunction with the UWA DC charging station to show how EV drivers would utilize fast DC charging stations remotely.

Paper Synopses

Below is a short synopsis of each paper and how it ties into the research questions:

Chapter 2: Analysis of Western Australian Electric Vehicle and charging station trials

These are the initial results of EV driving and charging behaviour from the Western Australian EV Trial and the Charging Station Trial, focusing on slower (Level 1 and 2) AC charging stations. This paper discusses how people are using EVs, where they are charging and how charging infrastructure is utilised.

Chapter 3: Acceptability of Electric Vehicles: Findings from a driver survey.

This was a survey performed on driver's acceptability of EVs based on data collected in the WA EV Trial and the Charging Station Trial. It discusses how people feel about driving EVs, highlighting their major concerns and difficulties.

Chapter 4: Electric Vehicle Battery Charging Behaviour: Findings from a Driver Survey

This was the analysis of a survey performed on EV charging preference based on data collected in the WA EV Trial and the Charging Station Trial. This paper discusses EV drivers charging preferences.

Chapter 5: Driving and charging patterns of electric vehicles for energy usage

These are the full results of EV driving and charging behaviour from the WA EV Trial and the Charging Station Trial. Focusing on all charging available including business, home and slower (Level 1 and 2) AC charging stations. This paper discusses how people are using EVs, where they are charging and how charging infrastructure is utilised.

Chapter 6: Leaving the grid—The effect of combining home energy storage with renewable energy generation

This chapter examines renewable energy generation and storage based on the UWA Future Farm, UWA Human Movement and Energy Made Clean (EMC), solar installations and German Wind Farm. This paper discussed how renewable energy sources could be used in conjunction with energy storage to charge EVs.

Chapter 7: REView – An Internet Portal for Monitoring Electric Vehicles and Charging Stations

This is an analysis of the REView software generated to automatically collect and analyse the data from all the trials. It discusses the usefulness of interconnectivity through data collection and standardisation in the roll out of EVs and Charging Station Infrastructure.

Chapter 8: A Comparative Study of AC and DC Electric Vehicle Charging Station Usage

This chapter combines the Charging station trial with the UWA Fast DC charging station and the RAC Electric Highway to give a comparative look at slower charging infrastructure in comparison to fast DC charging. These two trials, along with the data from the other trials, completed the picture for the various available charging infrastructures.

Summary

This research intended to look in greater depth at the future integration of EVs in Western Australia by examining the consumer, industry and engineering aspects of implementation in our state. The trials provided a clear picture of how EV users behave differently to ICE vehicle owners, how they interact with charging infrastructure, how energy was being consumed and how it can be offset with renewable technologies. From the insights generated, we determine the necessity and types of charging infrastructure, the standards that exist and should be adopted and the factors that affect EV uptake.

These series of papers were based on the trials, which were pilots performed in Western Australia with direct statistical results. This precluded the use of more in depth analysis, such as the Kaiser-Meyer-Olin (KMO) criterium, due to the lack of interdependency of the data collected [10]. Areas in which statistical results were affected by outlying factors are included.

Combined, these papers form an overarching analysis of the potential challenges to integrating an alternative to ICE vehicles which provide a reduced emissions transportation solution for the future of Western Australia.

References

[1] J. Johnson, "'Single Most Important Stat on the Planet': Alarm as Atmospheric CO2 Soars to 'Legit Scary' Record High," *Common Dreams*, 2019. [Online]. Available: https://www.commondreams.org/news/2019/06/05/single-most-important-stat-planet-alarm-atmospheric-co2-soars-legit-scary-record.

[2] "National Inventory Report 2017 - The Australian Government Submission to the United Nations Framework Convention on Climate Change - Australian National Greenhouse Accounts," 2019.

[3] “International Energy Agency,” 2018.

[4] “The state of electric vehicles in Australia - Climate Works Australia,” 2018.

[5] “V-Facts - Electric Vehicle Council industry agreement,” 2018.

[6] A. Krok, “EVs capture 58.4-percent market share in Norway in March,” *CNET*, 2019. [Online]. Available: https://www.cnet.com/roadshow/news/electric-vehicle-majority-market-share-norway-march/.

[7] “German EV incentives extended,” *Autovista Group*, 2019. [Online]. Available: https://autovistagroup.com/news-and-insights/german-ev-incentives-extended.

[8] F. Lambert, “California considers almost doubling its EV incentive as Tesla’s federal tax credit is phasing out,” *Electrek*, 2019. [Online]. Available: https://electrek.co/2018/09/26/california-ev-incentive-tesla-federal-tax-credit-phasing-out/.

[9] “Norwegian EV policy - Norway is leading the way for a transition to zero emission in transport.,” 2019. [Online]. Available: https://elbil.no/english/norwegian-ev-policy/.

[10] Stephanie, “Kaiser-Meyer-Olkin (KMO) Test for Sampling Adequacy,” *Statistics How To*, 2019. [Online]. Available: https://www.statisticshowto.datasciencecentral.com/kaiser-meyer-olkin/.

Published in: 2012 Australian Transport Research Forum ATRF,
Perth, Sep. 2012

ANALYSIS OF WESTERN AUSTRALIAN ELECTRIC VEHICLE AND CHARGING STATION TRIALS

Stuart Speidel[1], Fakhra Jabeen[2], Doina Olaru[2], David Harries[1], Thomas Bräunl[1]

[1]The University of Western Australia, School of Electrical and Computer Engineering, Perth, Australia

[2]The University of Western Australia, Business School, Perth, Australia

Email for correspondence: sjmspeidel@gmail.com

Abstract

An Electric Vehicle (EV) trial and an EV Recharging Research Project are being simultaneously undertaken in Perth, both the first of their kind in Australia. The EV trials involve 11 locally converted Ford Focus vehicles, while the EV Recharging Study involves the use of 17 charging outlets (final configuration 23 outlets) from Level 2 AC recharging stations. Data is being logged from both the vehicles and the recharging stations and is transmitted to a server at The University of Western Australia's (UWA) Renewable Energy Vehicle Project (REV), where it is used for statistical evaluation, analysis and modelling.

Key words: *Electric vehicle trial, charging station trial, charging network, charging statistics.*

1. Introduction

Rising fuel costs, growing public awareness and concern over environmental issues such as local urban air quality and global warming, combined with higher performance batteries mean that electric vehicles (EVs) are becoming an attractive alternative to internal combustion engine vehicles (petrol/diesel). Increased market penetration of electric vehicles will increase electricity loads, may place increasing demands on electricity grids. It will also require the installation, management and maintenance of compatible recharging infrastructure. Careful analysis, planning and management will be needed to reduce the costs of and to optimise placement of this recharging infrastructure and to minimise the impacts on electricity grids.

The goal of this study is to determine the optimal number and locations of electric vehicle charging stations in the area supplied by the main electricity grid in Western Australia, taking account the expected location, number and movement/ charging patterns of electric vehicles. This initial study shows electric vehicle usage patterns from telemetry data that has been collected from the WA electric vehicle trial and EV recharging project, consisting of eleven trial vehicles and 17 charging stations currently in use in Western Australia. As part of the recharging project, the UWA Business School is conducting EV driver satisfaction surveys as well as household surveys for potential EV buyers (Jabeen et al. 2012).

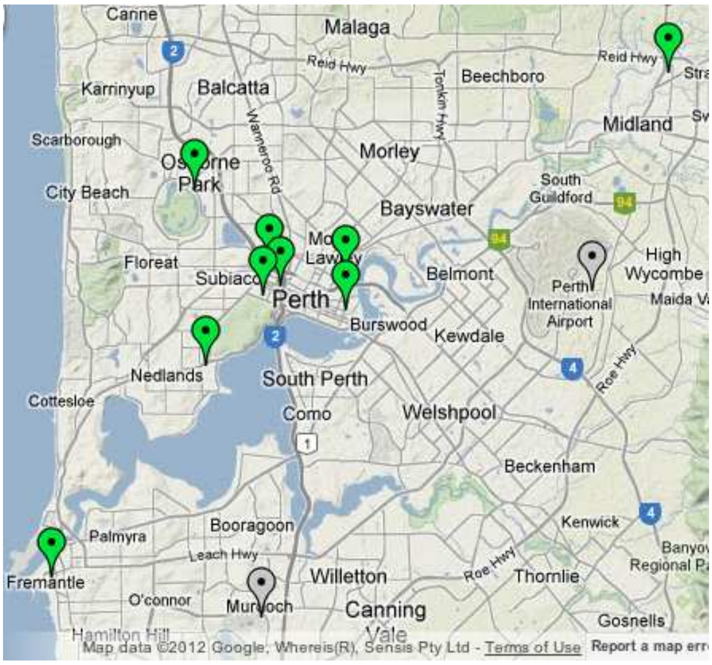
The trials form part of a road mapping exercise for business and government and is also being used to assist in the development of relevant standards and regulations (IEA 2011). The analysis of the vehicle charging times and locations may provide further insight into several EV research areas. While the likely slow uptake of electric vehicles (AECOM 2009; Järvinen et al.

2012) make it unlikely that electric vehicle charging will create significant problems for electricity grids such as the South-West Interconnected System (SWIS) in Western Australia (Mullan et al. 2011), the ability to compare the results of simulation studies of EV charging patterns based on vehicle fleet patterns with the results of real trials is very useful (EPRI 2007, 2011; Weiller 2011; Ashtari et al. 2012; Kelly et al. 2012; Shahidinejad et al. 2012). The trial results will also provide useful insights into the viability of vehicle-to grid-technologies and the ability to test the validity of analyses that have found that the high technology and infrastructure costs associated with some vehicle-to-grid (V2G) options are likely to be too large to render those V2G variants economically viability in most locations (Mullan et al. 2012).

2. EV Trial Cars

Beginning in early 2010 a consortium of eleven WA-based organisations have collaborated with the Renewable Energy Vehicle Project (REV), which is led and coordinated by the University of Western Australia (UWA) and local company CO2Smart. The organisations involved are learning through doing, with the goal of discovering viability and creating appropriate approaches to the emerging technology, as recommended by Garnaut (2011). Each of the participating companies purchased a standard 2010/11 model Ford Focus sedan and funded the conversion from petrol to electric drive, which was undertaken by WA company EV Works. The converted vehicles have a battery capacity of 23 kWh and a road-tested range of over 130 km. As automotive charging connectors were not available at the commencement of the trial, all vehicles were initially fitted with Australian three phase plugs (32A) as well as Australian single phase plugs (10A). The chargers in the vehicles will draw up to 4.8kW which allowed the vehicles to be charged from empty to full in about 4 hours or 10 hours, respectively.

Figure 1: Charging Station Network (using Google Maps 2012)

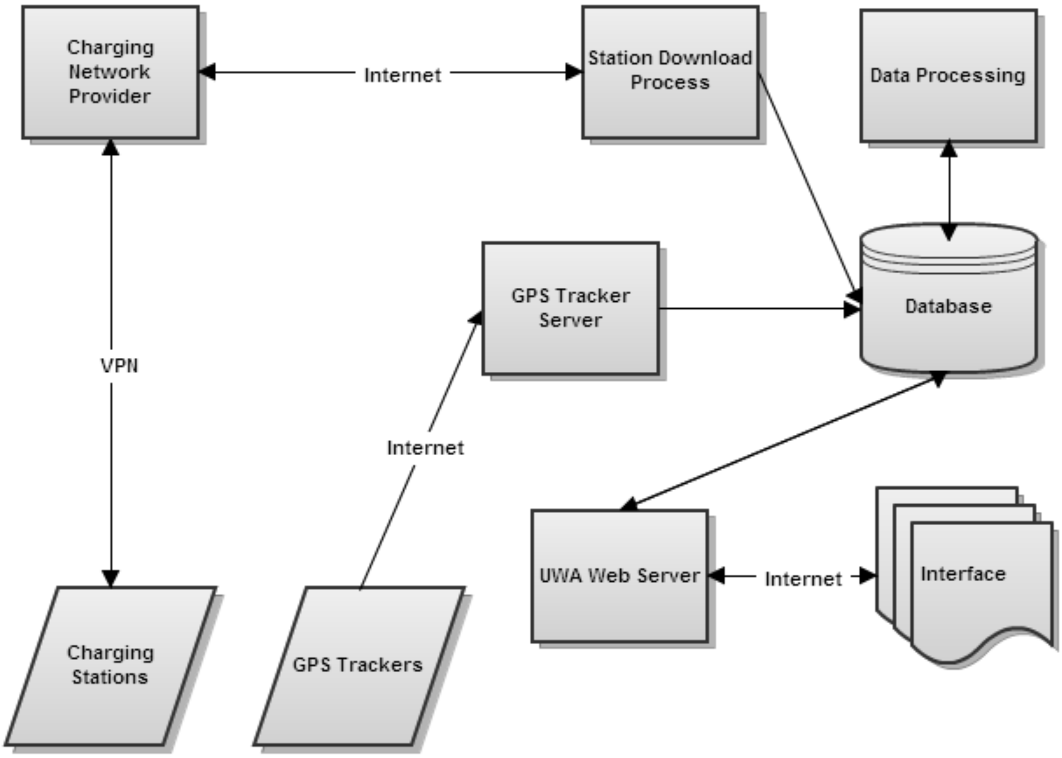


The trial subsequently adopted the European standard IEC 62196 Type 2 connectors and vehicle inlets (“Mennekes”), and vehicle inlets are currently being converted over to this new standard (IEC 2011). The advantage of the IEC 62196 Type 2 (“Mennekes”) over the US/Japan standard IEC 62196 Type 1 (“SAE J1772”), is that it supports single phase as well as three phase power, which the US/Japanese standard does not. Although Standards Australia has recommended that IEC 62196 be adopted as a whole, it has so far not made a recommendation on connector Type 1 or 2. Standard and regulations are important for electric vehicles and charging stations to ensure safety and to increase consumer confidence (Brown et al. 2010) and research aimed at informing new policies for introduction of EVs into Australia has been commissioned by the CSIRO (Dunstan 2011).

To measure the energy usage of the vehicles, GPS tracking devices with five digital inputs and one analogue input were installed in each of the cars and used to measure air conditioning status, heater status, headlights status, charging status, ignition status and the vehicle battery charge level. GPS positions and line inputs are uploaded onto the UWA server either every one minutes or ten meters (see Figure 2). For the last six months of the trial (ending 2012-08-22), 2,298,038 data rows were inserted into the database from the eleven EVs. The data is processed using a batch script and displayed to the trial participants via a web interface that displays telemetry data, driving and charging statistical heat maps for each and all of the vehicles. The data processing generates journey, charge and parking events.

Journeys have a starting time and location, ending time and location, total distance travelled air conditioning usage time, heater usage time, headlight usage time and the estimated battery. Journeys are started when the ignition is detected as being on and ending when the ignition is turned off.

Figure 2: System Diagram



Charges have a starting time, ending time, location, distance travelled (between charges), energy used (kWh), time charging and time maintaining charge. The charge events are generated starting when the vehicle charging door (the door covering the charging plugs) is opened and ending when the charging door is closed. When an EV is in a location and does not have either its ignition on a parking event is created from the last journey to the next journey. The parking events are then compared to charging events and if a vehicle charges while parking the charge is linked to the parking event.

The GPS tracking units log only when they have a GPS fix. A GPS fix is normally obtained when the antenna has an unobstructed view of the sky (Kaplan and Hegarty 2005). Throughout the trial, vehicles were parked on occasions within heavy indoor areas, such as parking structures or underground, and have been charged without an active GPS fix. When vehicles have a gap in their data logging of greater than 15 minutes and have a battery level increase of more than 10%, a charge event is created for the duration of the data loss. In those cases, the charge event is created entirely by estimation using the time the GPS signal was lost to the time the GPS was re-established as the start and end times. If a vehicle loses GPS fix while driving, the distance between the point before GPS loss and the point where the GPS is re-established and taken to be the distance travelled during the period.

There is also the possibility of a bad GPS fix caused by a weak or unreliable GPS antenna signal. In those cases, it is unreliable to confirm a vehicle’s position from one co-ordinate. All the coordinates gathered throughout the duration of the charge and within two standard deviations are therefore averaged out to make an estimated position. If that location is within a certain range of a known charging location, the coordinate is repositioned to the charging location.

3. EV Charging

3.1 Charging Stations

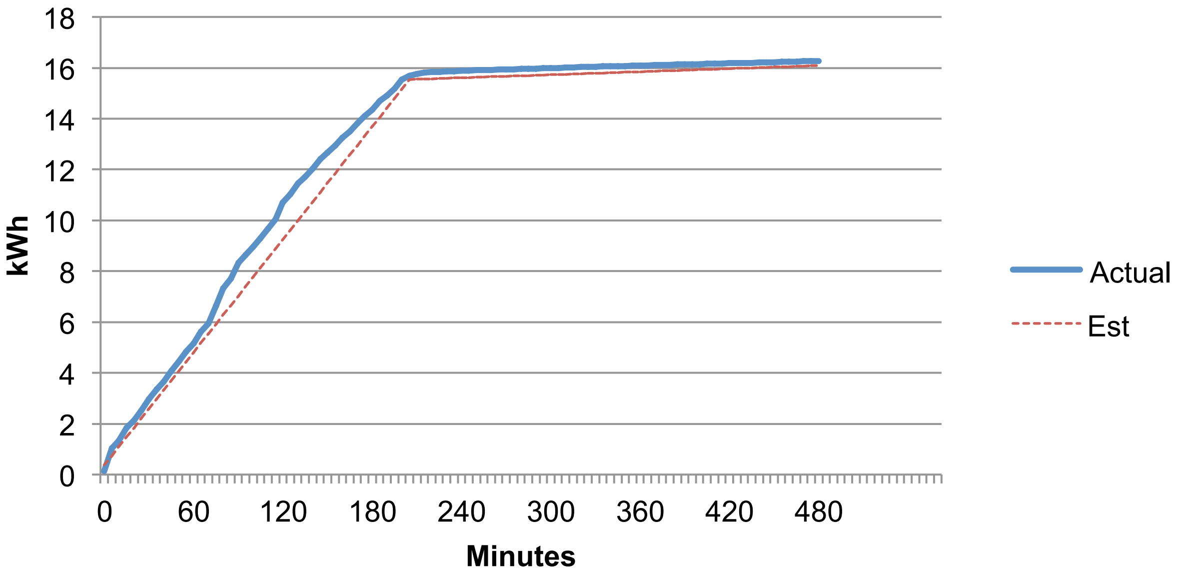
All charging station (locations shown in Figure 1) outlets log customer IDs, start time, end time, as well as the amount of energy used for potential customer billing. Charging station data is downloaded via GSM to an external server every four hours. The external server is checked every thirty minutes using a batch process and new charge events are downloaded to the server at UWA (see Figure 2).

3.2 Other Charing Points

When an EV is recharged at a charging station, the exact amount of electricity used (kWh) is recorded from the charging station’s meter. If an EV charges elsewhere (e.g. at home or at a business), or station data is missing, the amount of electricity used is approximated from the battery level of the vehicle, the recharging time, the distance the vehicle travelled before charging, and the level of power supplied. Each vehicle has a 30A charger installed, and the measured power loss from the power socket to the battery pack is 83%.

When the vehicle battery is full, the charger switches to a maintain charge mode, which maintains the batteries at full charge, the trial EV chargers use on average 0.12 kW to maintain the charge level. Once the battery charging level is estimated, the vehicle is assumed to be drawing power at that level for the remaining time that it is plugged-in. Figure 3 shows the energy drawn from a charging station with the energy meter readings (blue) and the estimated charging kWh (red). Using this information, the vehicle charging profile can be estimated.

Figure 3: EV Charging profile



3.3 Charging Locations

94% (1126 of 1203) of the recorded EV recharging events over the last six months of the trial occurred at 29 locations with a determined maximum power of 2.4 kW, 3.6 kW or 7.2 kW (10, 15 and 30 Amp sockets/stations at 240V), the latter information being obtained through site visits. The vehicles when charging at 10 or 15 amp sockets will draw 1.8kW and at 30 amp sockets and charging stations will draw at 4.8kW. The vehicles do not draw the full 2.4 kW at 10 Amp outlets for additional safety, related to results from audits showing 20% of Australian households having serious electrical safety faults (MEA 2011). Each location is also categorised as either:

1. Home, at a EV users residence
2. Business, at places of business such as work, but not at a charging station
3. Stations, at one of the installed charging stations

If a vehicle is recharged within a certain radius of a known charging station location, it is assumed to be charging at that location. The radius for each charging location is determined by the accuracy of the average GPS fix at that location. The other 7% of charging locations are labelled as unknown and are always assumed to be 2.4 kW.

3.4 EV Driver Influencers

The trials' electric vehicle drivers reported being influenced by the following factors, which may affect the statistical results:

- All EVs are company fleet vehicles and some organisations have restrictions on their use, such as not taking the vehicle home.
- Some EVs had dedicated drivers, whilst others were shared pool vehicles.

- Most EV drivers were not reimbursed for electricity usage in their homes.
- Four organisations had a charging station installed on their premises, specifically for their vehicle.

4 Driving Statistics

In 2010 the average distance a passenger vehicle travelled for business in Western Australia was 11,700 km per year or 32.0km per day (ABS 2011). The overall average for the trial over the last six months was 17.56 km per day, almost half than the West Australian average (Table 1). Over the time period, the EVs averaged 2 journeys per day. The estimated annual energy usage for the EV's is on average 1.13MWh, driving 17.56km and maximum of 3.33MWh driving 48.53km. The West Australian business average of 32km per day equates to 2.06MWh per annum. On average the air conditioner is on 29%, the lights 16% and the heater 3% of the time while driving.

Table 1: EV journeys (accumulated over six months)

Vehicle	Number of Journeys	Average Journey Time (mins)	Average Distance Travelled (km)	Average kWh Used (kWh)	Daily km (km)	Percentage		
						Air con	Lights	Heat
1	235	18.79	10.31	1.97	13.50	0%	21%	0%
2	252	19.49	9.75	1.86	13.73	0%	0%	1%
3	605	12.44	6.84	1.30	23.10	34%	22%	0%
4	120	23.77	14.25	2.72	9.53	34%	26%	18%
5	410	9.13	4.89	0.93	11.19	47%	19%	0%
6	432	13.70	5.52	1.05	19.21	78%	8%	7%
7	275	8.49	4.97	0.95	9.17	5%	1%	6%
8	354	13.03	7.67	1.46	15.41	27%	1%	5%
9	133	15.61	7.39	1.41	6.59	14%	13%	0%
10	712	19.39	12.22	2.34	48.53	63%	39%	0%
11	442	16.20	8.24	1.57	20.44	22%	22%	9%
Average	361	15.23	8.19	1.56	17.56	29%	16%	3%

The maximum average daily kilometre was 48.53, using only 37.33% of the vehicles maximum range. Over the last six months the maximum distance an EV drove in one journey is 71km, being the only journey greater than half of the vehicles range.

Figure 4: EV travel distance by time of day (accumulated over six months) for each of the 11 vehicles (1 – 11)

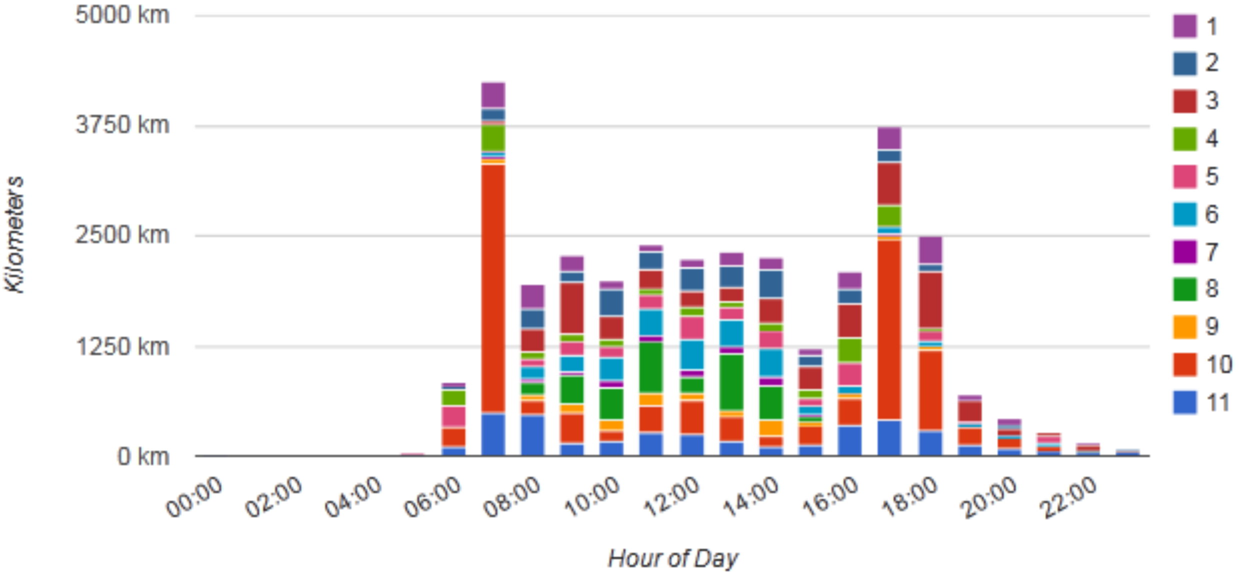
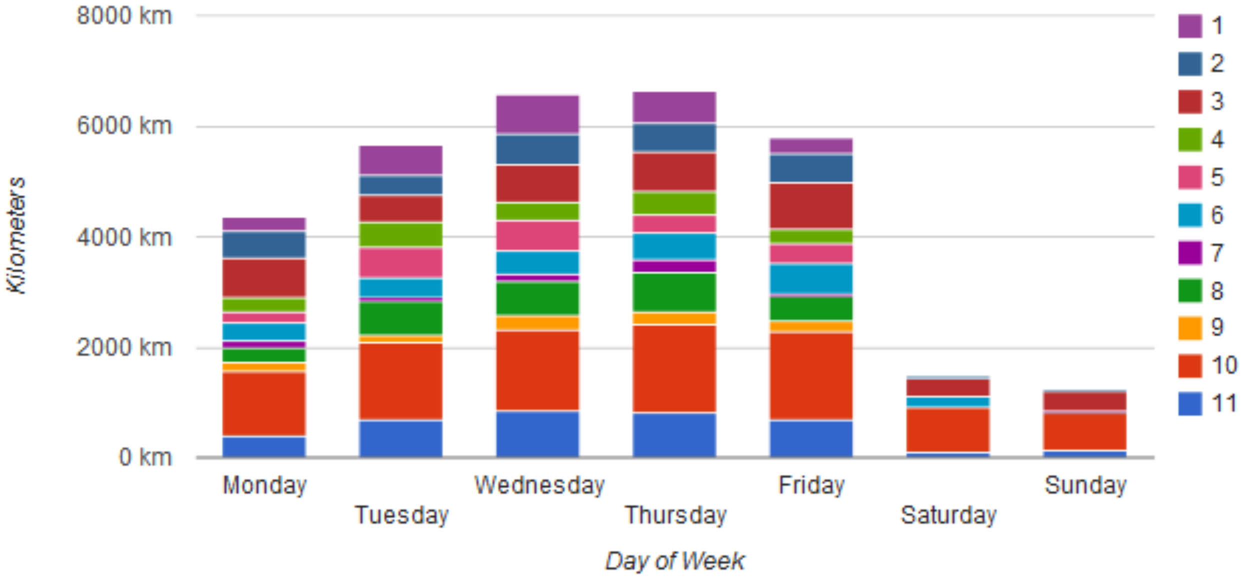


Figure 4 shows the distance travelled by the hour of day, with 92.28% of the total distance travelled occurring between 7am and 7pm. The peaks of distance travelled are at 7am and 5pm where vehicle 10 (which contributed 27% of the total km driven) arrives at and leaves work. Just over half (53.20%) of the total distance is travelled is undertaken between the hours of 9am to 5pm. The results in figure 4 are similar to the number of motorised trips by time of day in Melbourne reported by the CSIRO (2011) and the percentage of trips by vehicle each hour as reported by Clement-Nyns et al. (2010). The vehicles travelled 88% of their total distance on week days (see Figure 5), with most vehicles not being used on weekends.

Figure 5: EV travel distance by day of week (accumulated over six months) for each of the 11 vehicles (1 – 11)



5 Charging Statistics

The number of charging events over the last six months is 1,203, with 236 (19.62%) charges not charging to full. The charges are made up of 186 home charges, 392 station charges, 548 business charges and 77 in unknown locations. In these locations 541 charge events occurred at a high powered outlet (32A) and 585 at low power outlets (10A or 15A) with 77 at an unknown location and socket. Of the number of charges not full, 69 occurred at high powered outlets (13% of all high powered charges), 141 occurred at lower power outlet (24% of all low powered charges) and 26 occurred at an unknown location (34% of all unknown charges).

The charging statistics shown in Table 2 show the average charging time for an electric vehicle is 2:06 hours, while at a higher powered socket the EV's are charged in 1:26 hours and at a lower powered socket the vehicles are charged in 2:32 hours. After the vehicles are charged they remain plugged into the socket for 17:06 hours on average, of the total time parked only 12.9% is spent charging on average.

Table 2: Charging amounts and times (accumulated over six months)

Vehicle	Average kWh	Average Charging Time	Average Maintaining Time	Sum of charges at 10, 15 A outlet	Sum of charges at 32 A outlet	Average 10 Amp charge time	Average 32 amp charge time
1	4.16	2:05:41	34:03:59	81	11	2:00:32	0:41:12
2	12.27	2:41:18	36:37:08	2	47	1:56:12	2:34:37
3	5.41	1:45:50	2:02:43	104	100	2:13:34	1:06:26
4	9.05	1:21:28	54:34:51	0	61	None	1:18:46
5	7.13	1:17:54	5:47:43	5	83	0:03:55	1:20:54
6	7.73	3:44:34	31:21:08	79	0	3:43:52	None
7	5.46	2:30:04	13:42:11	24	1	2:35:46	0:13:16
8	14.33	6:36:34	29:20:12	51	0	6:36:34	None
9	2.08	1:15:04	55:43:09	58	1	1:08:36	0:02:08
10	8.01	2:17:16	6:07:38	109	99	2:23:13	1:54:15
11	4.89	1:12:20	5:41:32	72	138	1:00:23	1:10:07
Average	7.08	2:06:47	17:06:11	585	541	2:32:59	1:26:40

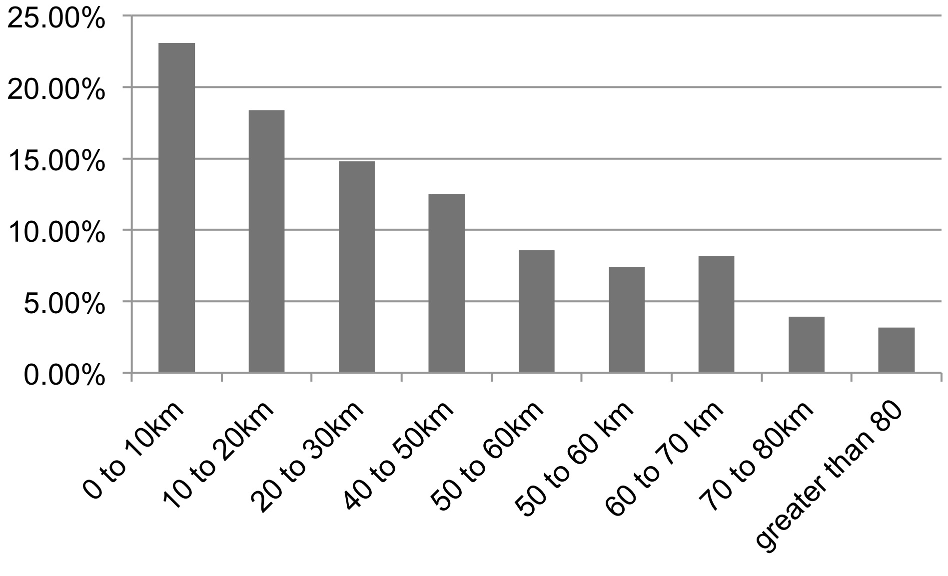
4.1 Vehicle Time Usage

Table 3: Vehicle time usage (accumulated over six months)

Vehicle	Total logged hours (hours)	Driving time per day (mins)	Average distance before charge (km)	Time driving	Time plugged in	Parking without plugged in
1	4307	0:24:17	18.02	1.69%	77.25%	21.06%
2	4293	0:27:27	57.81	1.91%	44.86%	53.23%
3	4308	0:41:44	19.00	2.90%	18.04%	79.06%
4	4305	0:15:54	26.32	1.10%	79.26%	19.64%
5	4300	0:20:41	22.13	1.44%	14.52%	84.04%
6	2980	0:46:53	27.87	3.26%	93.02%	3.72%
7	3578	0:06:19	18.39	0.44%	15.49%	84.07%
8	4228	0:26:11	51.75	1.82%	43.35%	54.83%
9	3580	0:13:36	10.12	0.94%	93.90%	5.16%
10	4304	1:15:53	36.23	5.27%	40.67%	54.06%
11	4274	0:40:12	16.26	2.79%	33.89%	63.32%
Average	4042	0:31:02	25.22	2.16%	49.01%	48.83%

On average, the EVs were not being driven for 97.84% of the time, or 23:29 hours per day. 49% of the hours where EVs were parked, they were also plugged in. Figure 6 shows the percentage of charges with distance travelled between charges. 84% of charges occur before the EV travels a distance of greater than 60km without charging.

Figure 6: EV charging distance travelled before charging (accumulated over six months)



4.2 Charging Location type

Table 4: Charging location type (accumulated over six months)

Vehicle	Time parked in known location	Time parked in unknown location	Charging probability at home	Charging probability at work	Charging probability at station	Charging probability unknown	Total Known locations used	Known locations charged at
1	83.68%	16.32%	27.27%	92.59%	53.33%	11.76%	17	11
2	75.46%	24.54%	0.00%	65.49%	0.00%	11.11%	12	4
3	72.77%	27.23%	20.63%	49.12%	90.53%	3.46%	11	9
4	80.13%	19.87%	Never	Never	95.08%	5.17%	2	2
5	77.19%	22.81%	66.67%	3.08%	97.67%	2.15%	4	4
6	95.77%	4.23%	Never	66.67%	0.00%	1.45%	3	2
7	98.65%	1.35%	66.67%	39.62%	100.00%	0.00%	8	5
8	49.24%	50.76%	Never	97.83%	0.00%	0.00%	3	1
9	89.55%	10.45%	0.00%	98.53%	100.00%	32.14%	6	5
10	88.79%	11.21%	37.37%	88.00%	0.00%	1.59%	7	5
11	49.77%	50.23%	34.78%	57.69%	86.08%	5.98%	11	6
Average	77.10%	22.90%	28.94%	63.28%	85.62%	3.89%	8	5

EVs driven and parked at the drivers' homes were recharged only 29% of the 463 times parked. EVs at the various known businesses locations were recharged 63% of the 806 times parked and those parking at charging stations charged 86% of the times 438 parked. EVs were parked at 2,058 different unknown locations and charged at those locations 4% of the times parked. On 77% of an EV's total parking time occurred in 8 different known locations and 49% of charging cases occurred in five different known locations.

Table 4 shows that for all the EVs in the trial, 96% of charges took place in each EVs top three locations, with on average 86% of charging taking place in one location for each EV. This can be interpreted as the EVs having one primary charging location where the majority of power is consumed.

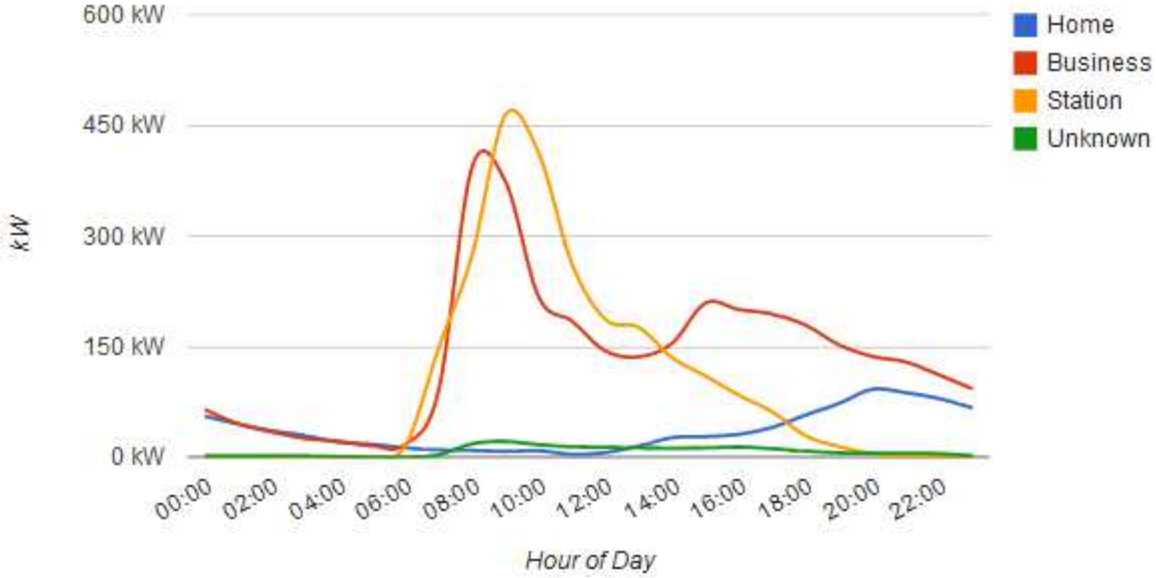
Table 5: Percentage of total charging energy (kWh) provided by top three used stations for each EV (accumulated over six months, each EV has different locations)

Vehicle	1	2	3	4	5	6	7	8	9	10	11	AVG
Location 1	73%	94%	56%	99%	100%	100%	82%	100%	89%	67%	83%	86%
Location 2	*8%*	*5%*	*15%*	1%	*0%*	*0%*	13%	0%	*7%*	28%	6%	8%
Location 3	5%	1%	13%	0%	0%	0%	2%	0%	3%	*2%*	*5%*	3%
Total of 3	87%	100%	84%	100%	100%	100%	98%	100%	99%	98%	93%	96%

4.1 Charging Power

The power (kilowatts) drawn by the electric vehicles over time of day are shown in Figure 4. The station and business charging power peaks at 8am and 9am as the electric vehicles are driven from the business the previous day, then returning the next morning and parked to charge for the total distance. At 3pm business power usage also spikes as the EV's are returned back to the businesses. At 8pm the home charging peaks as the vehicles are driven home to slow charge, and the power used slowly reduces throughout the night until the next morning. The business and station charging patterns is similar to the workplace charge load done simulated by Weiller (2011). Other simulations performed by Ashtari et al. (2012), Clement-Nyns et al. (2010), EPRI (2007) and Shahidinejad et al. (2012) use home charging profiles that don't reflect the results from the trial, where vehicles charge predominantly at business and stations (78% of charges).

Figure 7: EV charging distribution over day-time (accumulated over six months)



6 Conclusion

The early results from the EV charging gained from both the WA Electric Vehicle Trial and the ARC Linkage Project at UWA on EV Charging indicate that despite the initial concerns that electric utilities that EV charging will create a new demand peak in the early evening hours, this based on the results of this trial this appears to be highly unlikely in the case for fleet vehicles at least. The typical fleet car usage pattern has a charging in the mid-morning with a lower rate in the early afternoon hours. This almost exactly matches a solar photovoltaic (PV) pattern, so fleet EVs could ideally be offset by local solar PV systems.

The EV's charge primarily at one location (86%) and additional charging locations are not normally used as vehicles with a range of 130km can easily manage the maximum daily average of a trial EV, 48.53km, leaving and returning to their primary charging location. This is especially evident in that the EV drivers would only charge their vehicles 29% of the times parked at home, and only spend 23% of their time parking in unknown locations. Also in only 16% of charges had an EV travelled further than 60km, which is less than half of the vehicles range. It would appear that investment in additional level 1 or level 2 charging points outside of the primary charging location is unnecessary as it may not be fully utilised with a small number of active fleet vehicles.

When the vehicles use a business or stations as a primary location the peak power usage for the vehicles occurs between 8am and 11am with business having another peak at 4pm. The vehicles travelled mostly during the day with the distance peaking in the morning at 7am to 8am and in the afternoon between 5pm and 6pm, a pattern that is similar to Melbourne and overseas driving patterns. The similarity in the driving patterns of EV's and other passenger vehicles has shown that other research simulations of business charging can present accurate charging profiles.

In this trial the vehicles were only equipped for level 1 and level 2 charging points, and didn't fully utilise the level 2 infrastructure. Vehicles with fast DC charging capability, using connectors such as the IEC COMBO standard, to allow for fast-charging up to 50kW, and COMBO stations should be investigated in the future.

As the initial EV market over the next half decade is expected to be heavily biased towards the fleet market, these findings are even more important.

7 References

ABS (2011). Survey of Motor Vehicle Use. Australian Bureau of Statistics.

AECOM (2009). Economic Viability of Electric Vehicles.Technical Report, Department of Environment and Climate Change.

Ashtari, A., E. Bibeau, S. Shahidinejad and T. Molinski (2012). "PEV Charging Profile Prediction and Analysis Based on Vehicle Usage Data." Smart Grid, IEEE Transactions on **3**(1): 341-350.

Brown, S., D. Pyke and P. Steenhof (2010). "Electric vehicles: The role and importance of standards in an emerging market." Energy Policy **38**(7): 3797-3806.

Clement-Nyns, K., E. Haesen and J. Driesen (2010). "The Impact of Charging Plug-In Hybrid Electric Vehicles on a Residential Distribution Grid." Power Systems, IEEE Transactions on **25**(1): 371-380.

IEC (2011). Plugs, socket-outlets, vehicle connectors and vehicle inlets - Conductive charging of electric vehicles - Part 1: General requirements, International Electrotechnical Commission**:** 151.

CSIRO (2011). CSIRO Electric Driveway Project Plugging in: A Technical and Institutional Assessment of Electric Vehicles and the Grid in Australia Phase 1 Report.Technical Report.

Dunstan, C., Usher, J., Ross, K., Christie, L., Paevere, P (2011). Supporting Electric Vehicle Adoption in Australia: Barriers and Policy Solutions (An Electric Driveway Project Report).Technical Report, Prepared for Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) by Institute for Sustainable Futures, UTS: Sydney.

EPRI (2007). Environmental assessment of plug-in hybrid electric vehicles. Volume 1: Nation wide greenhouse gas emissions.Technical Report 1015325, Electric Power Research Institute. **1**.

EPRI (2011). Transportation Electrification: A Technology Overview.Technical Report, Electric Power Research Institute.

Garnaut, R. (2011). The Garnaut Review 2011: Australia in the Global Response to Climate Change. Australian National University, Canberra, Cambridge.

IEA (2011). Technology Roadmap - Electric and plug-in hybrid electric vehicles.Technical Report.

Jabeen, F., Olaru, D., Smith, B., Braunl, T., Speidel, S. (2012) Acceptability of electric vehicles: findings from a driver survey, Australian Transport Research Forum (ATRF), Sep. 2012, pp. (14)

Järvinen, J., F. Orton and T. Nelson (2012). "Electric Vehicles in Australia's National Electricity Market: Energy Market and Policy Implications." The Electricity Journal **25**(2): 63-87.

Kaplan, E. and C. Hegarty (2005). Understanding GPS Principles and Applications : Principles and Applications. Norwood, Artech House Books.

Kelly, J. C., J. S. MacDonald and G. A. Keoleian (2012). "Time-dependent plug-in hybrid electric vehicle charging based on national driving patterns and demographics." Applied Energy **94**(0): 395-405.

MEA (2011). Switch Thinking - Preventing Electrical Deaths in Australian Homes.Technical Report, Master Electricians Australia. http://issuu.com/master_electricians/docs/switch_thinking_report?mode=window.

Mullan, J., D. Harries, T. Bräunl and S. Whitely (2011). "Modelling the impacts of electric vehicle recharging on the Western Australian electricity supply system." Energy Policy **39**(7): 4349-4359.

Mullan, J., D. Harries, T. Bräunl and S. Whitely (2012). "The technical, economic and commercial viability of the vehicle-to-grid concept." Energy Policy **48**(0): 394-406.

Shahidinejad, S., S. Filizadeh and E. Bibeau (2012). "Profile of Charging Load on the Grid Due to Plug-in Vehicles." Smart Grid, IEEE Transactions on **3**(1): 135-141.

Weiller, C. (2011). "Plug-in hybrid electric vehicle impacts on hourly electricity demand in the United States." Energy Policy **39**(6): 3766-3778.

Published in: 2012 Australian Transport Research Forum ATRF,
Perth, Sep. 2012

ACCEPTABILITY OF ELECTRIC VEHICLES: FINDINGS FROM A DRIVER SURVEY

Fakhra Jabeen[1], Doina Olaru[1], Brett Smith[1], Thomas Braunl[2], Stuart Speidel[2]

[1]The University of Western Australia, Business School, M261, Perth, Australia

[2]The University of Western Australia, School of Electrical and Computer Engineering, Perth, Australia

Email for correspondence: 20873104@student.uwa.edu.au

Abstract

Plug-in Electric Vehicles (EV) offer a clean and cost effective means in the long run of driving short to medium distances within the city, even with the current high purchase cost. In Australia EV may be attractive as a second car in the multicar household. The acceptance of EV requires a change in behaviour – instead of re-fuelling, this vehicle requires battery charging each 140-160km, either at home or at specialised charging stations.

A limited number of EVs are being driven in Perth as part of the Western Australia Electric Vehicle trial (WA EV trial). The trial monitors the performance, benefits, infrastructure and practical implications of EV fleet. This paper explores the opinions and experiences of 43 of the participants. Factor analysis and multiple regression are applied to identify the main motivators and barriers in purchasing and using an EV.

Ninety per cent of respondents are confident about driving the EV; more than 45% take trips of more than 30km. While zero tailpipe emissions is the most desirable feature of EV, followed closely by home charging, the limited range of the vehicle is regarded as the most serious barrier to EV uptake. The overall satisfaction with the EV performance is high (an average score of 3.96 out of 5), although 13 participants experienced at least one technical difficulty, when driving the EVs in the trial.

Two latent constructs reflecting *environmental concerns, and technology learning,* along with EV benefits and technical difficulties experienced while driving an EV explain 59.2% of the variability of the willingness to purchase an EV as the next vehicle.

Key words: *Electric vehicle, multivariate analysis, drivers' attitudes.*

1. Introduction

The increased demand for fossil fuels requires investigation of other energy sources in transport planning. The plug-in Electric Vehicle (EV) is driven by electricity, using an electric motor instead of a petrol or diesel engine. EV has distinct characteristics, for example limited driving range, battery re-charging and zero tailpipe emissions. In addition, EV brings benefits in terms of low running costs. People's acceptance of new fuels and vehicles are determinants of the EV's place in the ensemble of vehicle technologies. The number of kilometres travelled on one charge and the need for frequent charging are factors influencing the purchase and use of an EV, along with the efficiency of the vehicle (weekly $ amount spent on travelling) and comfort. Individuals are likely to trade-off these features and their decision is also affected by attitudes, preferences, and habits.

Many Australian households use more than one car (ABS, 2008) so that the range limitation of EV may not be considered an issue when there is a second car available for long distance trips. With the low travel cost, EVs have the greatest potential for short trips within the city, but the charging requires good trip planning.

A limited number of EVs are in use as part of an EV trial in Perth, Western Australia. The trial monitors the performance, benefits, infrastructure, and practical implications of EV fleets. This study aims to find the perceived barriers to the purchase and use of both converted and commercially manufactured EV. A questionnaire was presented to the drivers in the WA EV trial. Because the vehicles in the trial are all converted EVs, only four respondents use manufactured EVs, with one having experience with both converted and commercially available EV. In terms of sample size, number of manufactured EV drivers is small due to the limited availability of EV in the Western Australian market.

In general, most of the drivers are confident in operating the EV, although 13 participants experienced at least one technical difficulty when driving the converted EVs in the trial. The overall satisfaction with the EV performance is still high with average score being 3.96 out of 5.

The two techniques used in this study include factor analysis and multiple linear regression. The results of the survey are analysed by testing a set of hypotheses through the regression model.

1.1 Aims of the Study

This study explores the drivers' behaviour through a survey with the following aims:

- Identifying drivers' perceptions about EV, and their willingness to purchase an EV;
- Ascertaining participants' attitudes towards the environment and adoption of new technologies;
- Informing the research program and assisting in refining the design of the questionnaire for the household survey that will be conducted separately. The EV driver survey serves thus as a pilot, testing two sections of the household questionnaire: a stated choice experiment and household attitudes towards EV. This study will assist in distinguishing the most relevant characteristics for EV purchase, as well as testing the reliability of several latent constructs necessary in capturing households' preference heterogeneity.

The next section discusses the literature about EV uptake, followed by a conceptual model for the adoption of EV (Section 3), and the data and methodology (Section 4). The findings of this research are discussed next (Section 5) and the last section conveys the conclusions of the study.

2. Previous Studies on the Uptake of Electric Vehicle

Considerable literature on the operating characteristics of EV (e.g. Voelker, 2009) and the work at UWA (Mullan *et al.*, 2010) has established that standard car models converted to EV can give excellent performance.

The studies to explore the potential demand for EV have started in different regions of the world. Most of the research work for EV uptake is in the USA. Kurani and Turrentine (1996) compared petrol and CNG with the hybrid and "neighbourhood" EVs (for 454 households) and found *home-recharging* will be successful. Half of the households mentioned that they would buy EV as their next new vehicle in *multi-vehicle households.* Kurani and Turrentine (1996) were also amongst the first researchers to incorporate attitudinal data in their modelling.
Golob and Gloud (1998), with 69 individuals, applied regression analysis comparing petrol and EV, and found EV likely to be used if average vehicle mileage is less than 28 miles/day. Another study in California (Hess *et al*., 2006) comparing internal combustion engine vehicles, EV and hybrid vehicles, suggested that EV can only compete in the market if they have a range greater than 353 miles – thus recommending increased driving range for EV acceptance.
Bolduc *et al*. (2008) conducted an experiment in Canada with 866 individuals, comparing petrol, alternative fuel, hydrogen fuel cell vehicle and hybrid EV. They used hybrid choice models including *perceptions and attitudes* and the structural and measurement equations for latent variables were simulated together. The hybrid choice model demonstrated its capabilities to capture: i) the environmental concerns; and ii) the appreciation of new car features. The behaviour towards charging of electric vehicles was not discussed; however, the latent constructs enriched the model's explanatory power.

Recent study by Lieven *et al.* (2011) in Germany applied correspondence analysis to rank eight types of cars (city, small, van, sports, luxury, etc.) for six types of uses (first vehicle for all uses, second for leisure, etc.). Their findings tell that *price* is the top priority for both conventional and EVs, with *range* ranked second. Performance, durability, environment, and convenience are given less priority. Only 4.2% of first car buyers chose EV and they rated price and range as a lower priority than non-EV potential buyers. Another recent research in vehicle type choice modelling is by Kuwano *et al.* (2012) in Japan, they designed a two stage model. In the first stage of decision making respondent was given a brief overview of EV features, and then asked whether to keep EV as one of the available choices. If the respondent decided to keep EV in the choice sets, a set of scenarios containing gasoline, hybrid-electric, and EV in the choice sets was displayed to the respondent; otherwise scenarios with only gasoline and hybrid-electric vehicle were given to the respondent. In this way social conformity was reflected in their model, and heterogeneity in the preferences was explained by the use of latent class models. In addition to the attributes that were considered by similar studies (such as purchase price, range, charging time, and operation costs), Kuwano *et al.* (2012) had market share as an attribute in their stated preference choice sets. With 384 respondents in Japan, Kuwano *et al.* (2012) found that *10% of respondents prefer to own an EV*, while 20.2% considered EV as an alternative in the choice experiments. They obtained three latent classes: *EV share rise, EV purchase price reduction, and EV performance improvement* (Kuwano *et al.,* (2012); page 7).

In summary, studies of EV acceptance have been increasing since their start more than ten years ago (Kurani and Turrentine, 1996; Brownstone *et al.,* 2000; Ahn *et al*., 2008), with the most recent research in this area being in the USA (Hidrue, 2010), Switzerland (Ziegler, 2010), Germany (Lieven *et al*., 2011), and Japan (Kuwano *et al*., 2012). The technology at the core of this study embodies significant advances and the study has the task of assessing how much these advances will improve acceptability of EV.

2.1 Consumer Behaviour Models on the Adoption of New Technologies

EV is a significant new technology; this makes it pertinent to explore EV adoption as "*new technology*" adoption. In the literature we find that technology adoption research includes variations for market inventions, in the field of information technology (IT), or both.

2.1.1 Technology Acceptance Model

Davis (1989) theorizes in the Technology Acceptance Model (TAM), that behavioural intention to use a system is determined by two factors: perceived usefulness and perceived ease of use. The term system here was taken as any *Information System*, and perceived usefulness is the extent to which an individual believes that the system will help to enhance his performance. The ease of use similarly indicates the extent to which an individual believes that using the system will not require extra effort to learn first. A theoretical extension of this model as TAM2 is defined (Venkatesh and Davis, 2000); it contributes by adding social influence constructs and also explores how perceived ease of use can be increased by helping the user to learn the system. This model has been used in different studies, as Lee *et al*. (2003) summarises its use in literature from 1986 till 2003.

2.1.2 Technology Readiness

The concept of *technology readiness* (Parasuraman, 2000) refers to the *people's propensity to embrace and use new technologies for accomplishing goals in home life and at work*. Parasuraman (2000) in collaboration with a company in the United States developed a Technology Readiness Index (TRI) as part of a technology readiness research program. Focus groups and interviews were conducted with the customers of companies from a variety of different technologies (e.g., financial services, e-commerce, online services, and telecommunications). After a number of analyses, a technology readiness scale was designed with four dimensions. The two positively supporting dimensions: *Optimism* and *Innovativeness* were classified as drivers, whereas the other two *Discomfort* and *Insecurity* were classified as inhibitors. The items in this TRI were further used by many researchers as a scale to measure self-service (e.g., ATM, bank by phone, and online banking) technologies adoption (James *et al*., 2005, Meuter *et al*., 2003), and also to explore the Internet home usage (Matthing *et al*., 2006). Both TAM and TRI consider the positive drivers of technology, however, in addition to TAM, TRI incorporates constructs with a negative effect in the adoption of new systems.

2.1.3 Technology Adoption Propensity

Ratchford and Barnhart (2011) reported on the assessment of consumer propensity to adopt new technologies. This research primarily considers the adoption of new technology by consumers in the market, while TRI focused mainly on specific technologies (for example, computers, or Internet). When buying a new technology the decision is made based on the benefits, and the time and effort consumers spend in learning and absorbing the new technology (Ratchford and Barnhart, 2011). The precise forecasting of technology products requires measurement of both positive and negative attitudes towards the technology. Ratchford and Barnhart (2011) recently developed a Technology Adoption Propensity (TAP) index containing 14 items, significantly shorter than TRI with 36 items.

2.1.4 Post Adoption Behaviour

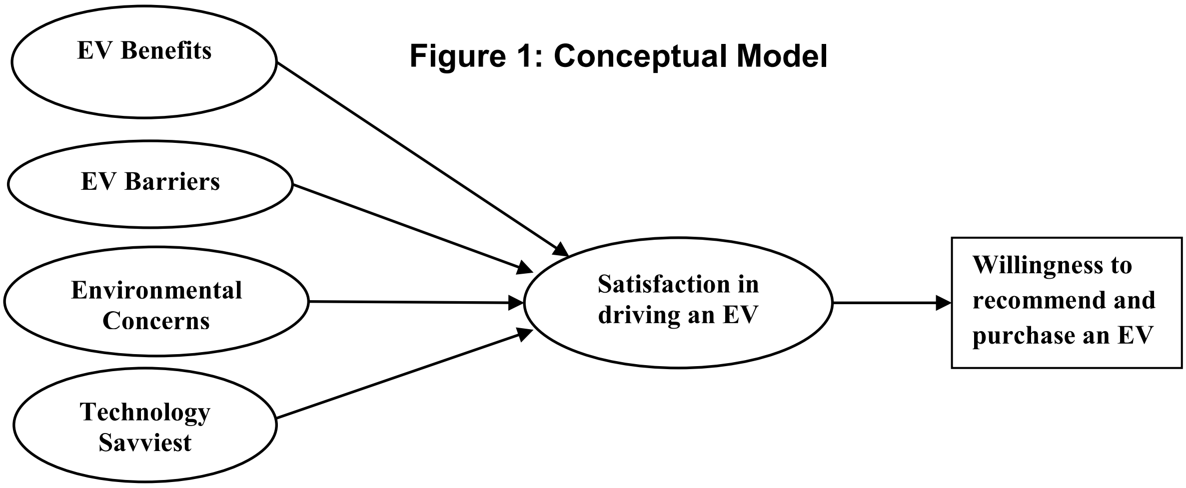
Huh and Kim (2008) studied the role of post-adoption behaviour and experimented with young people and early adopters. On the other side, Son and Han (2011) indicated that technology readiness of the consumer (i.e. how well a consumer is prepared for the new technology) has an impact on the post-adoption behaviour. Gatignon and Robertson's (1985) suggested that diffusion of technological innovations will depend on consumers developing new knowledge and new patterns of experience.

3 A Conceptual Model for the Adoption of Plug-in Electric Vehicles

Drawing on the above literature, a set of latent constructs were identified through which the acceptability of Plug-in Electric Vehicles by the drivers' in the WA EV trial can be assessed. Thus, the objective of this study is to determine what contributes for the drivers' attitudes and perceptions of EV, and also to find which EV driving experiences can affect their propensity to adopt EV.

The specific questions we explore in this research refer to: the direct impact of EV benefits, technical difficulties experienced while driving EV, along with effects of the attitudes towards environment and technology adoption (measured using latent constructs) on the willingness of the drivers to recommend and purchase an EV. The survey instrument was designed according to the conceptual model given in Figure 1. While the purpose of the overall research is to test a mediating model (EV benefits and barriers, environmental concern, and technology learning impact on the overall satisfaction while driving an EV, which in turn allows predicting the willingness to recommend and purchase an EV) for this paper, we test a direct model with all predictors affecting the willingness to recommend and purchase an EV.

Figure 1: Conceptual Model



The primary hypotheses of this study include:

H1: Drivers confident in the environmental performance and efficient use of energy of EV are more likely to recommend and purchase an EV.

H2: Drivers showing concerns for environmental changes are more likely to recommend and purchase an EV.

H3: Drivers ready to adopt and learn new technologies are more likely to recommend and purchase an EV.

H4: Perceived EV benefits influence positively the willingness to recommend and purchase an EV.

H5: Experienced technical difficulties while driving an EV influence negatively the willingness to recommend and purchase an EV.

H6: Overall, drivers' satisfaction with EV reflects the willingness to adopt EV as a future car. For this paper the satisfaction with driving an EV is tested as one of the independent variables, as this is not mediating model rather a direct model is tested with all predictors affecting the willingness to adopt EV as a future car.

4 Data and Methodology

In order to design the survey questionnaire, a focus group was conducted in November 2011 with 11 EV drivers at The University of Western Australia. The drivers discussed their EV driving experiences and perceptions towards EV as a new technology. Overall, they were satisfied with the trial EV performance and showed confidence towards its acceptance. The participants indicated the pros and cons of EV in the trial. The advantages of EV as discussed in the focus group include: *smooth and quiet operating drive, good torque, resource management, sustainability, being a new technology (innovative) but appearing or driving like a normal car, clean energy with no emissions, low running cost, minimal service cost or no need to go for oil-checks, free reserved parking, efficiency.* The drivers also discussed the drawbacks and concerns that they had while driving EV: *limited range, finding a charging station, recharging time, trip planning, range indicator problems, and technical problems like regenerative braking, acceleration etc*. These barriers also affected the willingness of other drivers to become part of the trial, when presented in the induction process for EV usage. The participants also indicated the factors that might affect EV performance in the market, such as *range, performance, place and time required for recharging, substantial price, limited choice of EV models, and their resale value*.

In December 2011, an online survey was deployed and sent to all EV drivers in Perth, WA. The experiences of the drivers in the focus group helped the design of the questionnaire. The instrument included four sections: 1) EV characteristics; 2) drivers' experiences; 3) attitudinal questions; and 4) background questions. The socio-demographics in the survey included the age, sex, education of the respondents, and number of cars at home. Since the drivers in the trial did not purchase the EVs themselves, the income variable was deemed irrelevant. The questionnaire also asked drivers about the technical problems encountered when driving the EV, as well as what do they perceive the most and the least desirable features of EV. The vehicles in the trial are all converted EVs, thus only a limited number of drivers outside the trial had experiences with manufactured EVs. The overall satisfaction of driving EV was also included in the questionnaire.

4.1 Survey Design and Data Collection

The drivers in the EV trial filled in *an online* survey, with 43 respondents completing all questions. Although this is a small number of respondents, the response rate was high (and the sample appropriate for representing the EV drivers in WA) considering that only few organisations in the trial have started to use EV, with not all the respondents using it on a regular basis. Among these 43 respondents, four respondents experienced driving commercially manufactured EV, while rest of respondents are drivers of the converted EV..

The socio-demographics in survey (Table 1) show that the majority of respondents are male drivers (67.4%), and a number of respondents (73%) own 2 or more cars. Twenty-two respondents are over 40 years and 28 have tertiary education.

More than 80% of drivers showed satisfaction in driving EV, with 34.1% being extremely satisfied. This is a positive indication towards EV acceptance in the WA EV trial, where 24% of respondents drive more than 50km, 39% drive 21-50km, 27% drive 10 to 20km, and only 11% drive less than 10km in a single trip.

Table 1: Information about Respondents

Variable	%	Count
Gender		
Male	67.4%	29
Female	32.6%	14
Age		
17-22	9.3%	4
23-29	20.9%	9
30-39	18.6%	8
40-49	18.6%	8
50-59	20.9%	9
60+	11.6%	5
What is your highest level of education?		
Year 12	9.3%	4
College/Professional qualification	25.6%	11
University Bachelor Degree	48.8%	21
Masters or PhD	16.3%	7
How many vehicles do you have at home?		
1	27.9%	12
2	48.8%	21
3 or more	23.3%	10

"*Zero-tail-pipe emissions*" was considered the most desirable feature suggesting that the drivers are concerned about the environment, followed by *"low running cost"*, then "*reliability*", "*low-maintenance*", and "*home-charging*". *"Low level of noise"* is also suggested as a desirable feature of EV by the drivers in the trial. In terms of perceived barriers for EV uptake, the respondents indicated the "*limited range*" and "*purchase cost*" as the most serious limitations, followed by "*recharging infrastructure*" and "*recharging time*", with "*reliability*" the least serious barrier.

As informed by the focus group, the questionnaire presented a list of technical problems with EV, from which the participants had to select the ones they encountered while driving EV. Forty-two respondents answered this question, 52% respondent indicated "*Power-steering failure*", "*no regenerative braking*" and "*range indicator errors*", while 10 respondents reported other faults that are related to *charging, braking faults, motor overloading, and gearbox* problems.

Recognising the role of attitudes and preferences in explaining behaviours, the survey included a set of latent constructs regarding EV benefits, environmental concerns, adoption of new technologies, and willingness to recommend and purchase an EV. Since the objective of this survey is to investigate and test the role of these latent constructs against the *willingness to purchase an EV*, the analysis included two stages: i) exploratory factor analysis to test the validity of the latent constructs (latent factor scores were derived for use in the subsequent analysis); ii) *multiple linear regression*, for simultaneous assessment of the linear interrelationships between predictors for willingness to purchase EV.

4.1 Exploratory Analysis of Attitudes towards Electric Vehicle

To test the drivers' behaviours and attitudes towards EV, items reflecting several latent constructs were included in the survey. These constructs refer to: EV benefits, environmental concerns, adoption of new technologies, and willingness to recommend and purchase an EV.

The latent constructs' items were designed as a set of five level *Likert-Scale* questions ranging from strongly agree to strongly disagree. After an Exploratory Factor Analysis (EFA) stage, uni-dimensional constructs were tested.
During the analysis of the constructs, it has been found that few construct items were weak and they will be redefined for the household survey. Each construct is discussed in detail below.

4.1.1 Environmental Concern

This construct showed strong relationships among the variables. The basic assumptions of factor analysis are satisfied, with a Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy of ***0.707*** indicating a strong construct. The *alpha factoring* extraction method was used to maximise the construct reliability; factor loadings of each element in this construct are above 0.5, as shown in Table 2.

The analysis of results showed that 90% respondents agreed that it is now the real time to worry about our environment and this requires our immediate efforts. A large number (69.8%) of respondents believed that climate change is not a myth; this shows that respondents are concerned about climate change and air pollution effects. Approximately 63% of respondents showed willingness to spend extra time or pay more for products and services, only to save the environment.

Table 2*: Environmental Concern* Factor Loadings

Items	Factor Loadings
Now is the real time to worry about the effects of air pollution.	**0.795**
I am concerned that future generations may not be able to enjoy the world as we know it currently.	**0.757**
Saving the environment requires our immediate efforts.	**0.718**
I am willing to pay more for products or services only to save the environment.	**0.714**
I am willing to spend extra time only to save the environment.	**0.622**
Vehicle emissions can destroy our flora and fauna.	**0.534**

For this construct, the reliability coefficient, Cronbach's Alpha has a value ***0.832,*** suggesting consistency of the entire scale (Hair *et al.,* 2010).

4.1.2 Technology Adoption

This is a very important construct, already tested in literature investigating the adoption of EV as new technology (Ewing and Sarigollu, 2000). Our analysis showed that multiple constructs may emerge (the items were not correlated significantly for a unidimensional factor), and we selected here to report the strongest one – *"technology learning"*.

Overall, the survey responses are convincing about the relevance of technology adoption in further uptake of EV. For example, 90% respondents believed that using new technologies makes our life easier, and 70% respondents felt that new technologies give more control over our daily life. Nearly 77% of respondents showed an excitement for learning new technologies, while 80% of the drivers agreed that keeping up with the new knowledge or technologies is necessary.

When exploring the trendy or being fashionable tendency of the respondents, we found that almost 30% of respondents are savvy-trendy adopters, based on their response that "taking up new technologies makes one trendy", and that "being fashionable means having up-to-date knowledge of the techno-world". Approximately 44% of respondents did not agree that new technologies cause more problems than they solve.

As indicated, the EFA suggested more than one dimension, but only three items, with higher commonalities and factor loadings were further retained. They are shown in Table 3.

Table 3: *Technology Learning* Factor Loadings

Items	Factor Loadings
I am excited to learn to use new technologies.	**0.758**
Reverse (Things have become so complicated today that it is hard to understand what is going on in this techno-world)	**0.703**
I love gadgets	**0.601**

The measure of sampling adequacy (KMO) value ***0.669*** and a Cronbach's Alpha of ***0.703*** indicated that this structure for the one-dimensional *Technology Learning* construct is appropriate.

4.1.3 EV Benefits and Challenges

The most important EV benefits, identified by respondents, included: convenience of home battery recharging and reduced average travel cost per trip. The respondents are also comfortable with recharging their EV at public stations, although almost half of the respondents need to do a lot of planning of activities when they drive EV.

In regard to EV technical difficulties, only 20% of the respondents believed that EVs have problems with the acceleration; while 29% disagreed that EVs incur significant maintenance costs.
None of these two constructs, *EV benefits* or *Technical problems associated with EV* had adequate reliability in this sample, and consequently they were not used in this analysis.

4.1.4 Willingness to Recommend and Purchase an EV

This construct showed strong relationships among the variables (KMO=***0.725***). Factor loadings of the elements in this construct (all above 0.8) are given in Table 4. The Cronbach's Alpha had the highest value of all constructs, ***0.910***.

Table 4: *Willingness to recommend and purchase an EV* Factor Loadings

Items	Factor Loadings
I prefer to use EV over any other type of cars.	**0.911**
I would recommend EV to others.	**0.828**
I would buy an EV as my next car.	**0.837**

The results of the analysis show that approximately 65% of respondents would recommend EV to others. Buying an EV as a next car is chosen by 27.9% of respondents, while 35% of respondents would prefer to use EV over any other cars. This percentage of driver's showing a preference to use EV over any other type of cars indicates a positive attitude towards EV and acceptability of the electric car.

5 Regression Model for EV Adoption

Once all the possible factors were identified, the next step was to quantify the effect of different factors in the willingness to adopt EVs. As suggested in the hypotheses, the set of independent variables identified for this model include: environmental concern, attitudes towards technology learning, EV benefits, EV technical problems, being a savvy-trendy adopter, and having confidence in driving EV. The socio-demographics considered in the analysis include age, gender, and education.

The regression model initially tested all the independent variables, but the high correlations among the explanatory variables resulted in multicollinearity issues (Hair *et al.*, 2010). The correlations between independent variables and the willingness to purchase and recommend an EV are given in Table 5.

Table 5: Correlations between Independent Variables and Willingness to Recommend and Purchase an EV

	Independent Variables	***Willingness to recommend and purchase an EV***	**Significant Cross Correlation Coefficients between potential explanatory variables**
		Correlation Coefficients	
AGE	What is your age (years)?	**0.143**	
HE	What is your highest level of education?	**-0.152**	
TechL	*Technology learning construct*	**0.157**	
EnvC	*Environmental concern construct*	***0.250***	
Conf	How confident are you in the environmental performance and efficient use of energy of EV?	**0.561****	**EV_B1 (0.448*), EV_B2 (0.434*), OvSat (0.475**)**
Tech_B	New technologies give more control over our daily life.	**-0.004**	
TFas	Being fashionable means having up-to-date knowledge of the techno-world.	**0.077**	
LessM	Reverse (I spent a significant amount of money to fix my EV in the last 3 months).	**0.476****	**AccP (0.454*), EV_B1 (0.482**), EV_B2 (0.449*), OvSat (0.441*)**
AccP	I believe EV has no problems with acceleration.	**0.346***	**LessM (0.454*)**
EV_B1	Battery recharging at home is convenient for my EV.	**0.594****	**Conf (0.448*), LessM (0.482**), EV_B2 (0.509**), OvSat (0.552)**
EV_B2	EV driving reduces my average travel cost/trip.	**0.491****	**Conf (0.434*), LessM (0.449*), EV_B1 (0.509**), OvSat (0.560**)**
OvSat	Overall, how satisfied are you driving an EV?	**0.634****	**Conf (0.475**) , LessM (0.441*), EV_B1 (0.552**), EV_B2 (0.560**)**

*** p<.05 ** p<.01**

Table 5 shows that all independent variables (Conf, LessM, EV_B1, EV_B2, OvSat) have moderate correlations with each other. Overall satisfaction in driving an EV (OvSat) is related to EV Benefits (EV_B1, EV_B2), and to being confident in environmental performance and efficient use of EV energy (Conf). Similarly, a lower amount of money spent to fix EV in last 3 months (LessM) has a positive impact on the overall satisfaction (OvSat), and perceived EV benefits (EV_B1, EV_B2).

One of the remedies for multicollinearity is to omit one or more highly correlated variables, and identify other independent variables to help the prediction (Hair *et al.*, 2010). To address multicollinearity and given the reduced sample size, a backwards elimination procedure was applied. Two different models were tested, with overall satisfaction and EV benefits being the response variables (Tables 6 and 7).

5.1 Multiple Linear Regressions' Results

With a coefficient of determination R^2 =0.643, the regression model presented in Table 6 confirms a subset of our hypotheses. The standardised coefficients indicate the relative importance of predictors in the same units or standards, regardless of the measurement scale used for the independent variables (Hair *et al.*, 2010). When considering the socio-demographics, age played a significant positive role in the model, with younger people less likely to recommend and purchase an EV (beta for AGE is 0.185). This might be due to the reason that more than 30% of respondents have an age of 50 years or above. The AGE variable has even more significant value in Table 7 where beta is 0.260.

The first hypothesis of this study (drivers confident in the environmental performance and efficient use of energy of EV are more likely to recommend and purchase an EV), is confirmed with the standardised coefficient as 0.262. The third hypothesis shows mixed results with one positive coefficient (technology learning 0.198) and a negative one (control given by technologies -0.287). Hypothesis 5 is also confirmed with a significant negative coefficient and the highest beta in absolute terms (0.367). The satisfaction variable (OvSat) comes next (0.336), confirming hypothesis 6 that overall, drivers' satisfaction with EV reflects the willingness to adopt EV as a future car.

Table 6: Regression Model with Satisfaction Variable as Predictor

	Dependent Variable: *Willingness to recommend and purchase an EV*	**Unstandardized Coefficients**		**Standardized Coefficient**	**Significance**
		B	**Std. Error**	**Beta**	
	Independent Variables				
	(Constant)	-0.716	0.815		0.385
AGE	What is your age (years)?	0.127	0.072	0.185	0.086
Conf (H1)	How confident are you in the environmental performance and efficient use of energy of EV?	0.370	0.177	0.262	**0.044**
Tech_B (H3-A)	New technologies give more control over our daily life	-0.371	0.146	-0.287	**0.016**
TechL (H3-B)	*Technology learning construct*	0.281	0.174	0.198	0.114
Tech_Diff (H5)	I spent a significant amount of money to fix my EV in the last 3 months	-0.387	0.125	-0.367	**0.004**
OvSat (H6)	Overall, how satisfied are you driving an EV?	0.338	0.131	0.336	**0.014**

Note: Parameters significant at 0.05 level in bold.

As discussed in more detail in the next section, satisfaction is a mediator between the EV benefit, EV barriers, and technology learning constructs, and the willingness to recommend and purchase an EV.

The regression model in Table 7 also tests hypotheses of this study, but this time after excluding the overall satisfaction from the list of predictors; independent variables that were not significant were removed from the model, one at a time, while exploring the impact of the rest of the variables. The final model, containing only significant variables, is given below. It has the R^2

value of 0.592, this indicates that variables in this model explain 59.2% of the variability in the willingness to recommend and purchase an EV.

The second hypothesis in this study (drivers showing concerns for environmental changes are more likely to recommend and purchase an EV) is not confirmed by the model, but this may be due to the sample size and limited variability in the construct (the average factor score is 3.71, with a standard deviation of 1.02). Ewing and Sarigollu (2000) found that *the consumers accepted the environmental impact of clean fuel vehicles, but the vehicle's standards cannot be compromised.*

Again, hypothesis 3 does not have full support with the question on technology's control over lives displaying a negative relationship. This negative coefficient was unexpected, however it might be due to the fact that most of the respondents in this study have an experience of driving converted EVs, and not commercially manufactured EVs. Another possible reason might be the word "control". This item needs to be reconsidered for the household survey and perhaps instead of "control over our daily life", the question needs to be reformulated to include "enable us" or another positive phrase (for example "*Using new technologies in our daily lives makes life easier.*")

Table 7: Final Regression Model

	Dependent Variable: *Willingness to recommend and purchase an EV*	**Unstandardized Coefficients**		**Standardized Coefficient**	**Significance Level**
		B	**Std. Error**	**Beta**	
	Independent Variables				
	(Constant)	0.411	1.416		0.773
AGE	What is your age (years)?	0.180	0.082	0.260	**0.036**
EnvC (H2)	*Environmental Concern Construct*	0.224	0.172	0.150	0.201
Tech_B (H3-A)	New technologies give more control over our daily life	-0.382	0.172	-0.299	**0.034**
TechL (H3-B)	*Technology learning construct*	0.387	0.178	0.278	**0.037**
EV_B1 (H4-A)	Battery recharging at home is convenient for my EV.	0.266	0.124	0.308	**0.040**
EV_B2 (H4-B)	EV driving reduces my average travel cost/trip.	0.284	0.147	0.268	0.062
Tech_Diff (H5)	I spent a significant amount of money to fix my EV in the last 3 months	-0.305	0.151	-0.289	**0.051**

Note: Parameters significant at 0.05 level in bold.

The fourth hypothesis (H4) of the study (perceived EV benefits influence positively the willingness to recommend and purchase an EV) is confirmed, with EV_B1 and EV_B2 presenting beta coefficients of 0.308 and 0.268, among the highest in the model. Thus, this demonstrates that perceived EV benefits (low driving cost and home-charging) influence positively the willingness to recommend and purchase an EV. This is consistent with the previous literature: e.g., Kurani and Turrentine (1996) identified the "*home-charging*" as a key benefit of EV.

The fifth hypothesis (H5), regarding the relationship between experienced technical difficulties while driving an EV and the willingness to recommend and purchase an EV, is confirmed as well, with a negative coefficient and a beta value of -0.289. Technical difficulties experienced while driving an EV act as a deterrent for EV uptake. This is well supported by the literature. Dagsvik *et al.* (2002) indicated that *alternative fuel vehicles can compete with petrol cars if maintenance and refuelling infrastructures for alternative fuel vehicles are well established*. Again these coefficient values could be different if there were more number of respondents driving commercially manufactured EVs (with less technical difficulties) instead of converted EVs.

5.2 Discussion and Future Research

The independent variables taken into account in this study were derived from literature and were further refined after the focus group. This study primarily explored the behaviours and experiences of the drivers already using the EV, in the WA EV trial. With a limited number of respondents (N=43) a number of hypotheses were tested and confirmed. One of the limitations of this study is that among small set of respondents (N=43) the majority of drivers used converted EVs, only 4 drivers had experience of driving manufactured EVs. Thus, the results would intuitively be different if the number of commercially manufactured EV drivers was larger. At the same time, this limitation does not impact the main objective of the study that is to discover the drivers' perceptions and attitudes towards EVs, and to determine how their experiences might affect acceptability of Electric Vehicles. The weakness of the few constructs was also noted as another limitation and these constructs will be revised for the upcoming household survey.

Since the satisfaction variable seems to be a mediator between perceived EV benefits, EV technical difficulties, attitudes towards technologies constructs and willingness to recommend and purchase an EV, the next step will be to assess these relationships using structural equation modelling (SEM) approach (Meyers *et al*., 2006). On account of small sample size, this was not currently possible, but with a higher number of respondents from the household survey it might be possible in the future.

6 Conclusion

This research explores the EV drivers' behaviour and their perceptions and attitudes towards new technologies. Experiences of drivers in the trial are useful for exploring the impact of EV benefits and of their technical difficulties on the acceptance of EV. The drivers showed confidence in the EV's environmental performance and efficient use of energy. The range is a serious barrier to EV uptake, with almost half of drivers indicating that they require significant trip planning especially for trips longer than 30km.

The analysis of the drivers' survey also aimed to refine the latent constructs such as technology adoption and environmental concern. With the data from the drivers' survey the reliability of the constructs was assessed and items with low value of loadings are being revised. Although the environmental concern appeared non-significant in the regression models, the literature identified it as a key construct, and we will consider it in the household survey. Another supporting argument for environmental concern construct is that the "*Zero-tail pipe emissions*" is ranked as the most desirable feature of EV by the drivers in the trial.

The results of this analysis will inform the household survey, and these constructs will be presented with further improvements, in the pilot household survey.

7 References

ABS. (2008). 4102.0 - Australian Social Trends Retrieved 27 May 2011, from http://www.abs.gov.au/AUSSTATS/abs@.nsf/Lookup/4102.0Chapter10102008.

Ahn, J., Jeong, G., & Kim, Y. (2008). A forecast of household ownership and use of alternative fuel vehicles: A multiple discrete-continuous choice approach. *Energy Economics, 30*(5), 2091-2104.

Bolduc, D., Boucher, N. and Alvarez-Daziano, R. (2008) “Hybrid Choice Modeling of New Technologies for Car Choice in Canada”, *Transportation Research Record,* 2082, 63-71.

Brownstone, D., Bunch, D.S., and Train, K. (2000) “Joint mixed logit models of stated and revealed preferences for alternative-fuel vehicles”, *Transportation Research* B, 315-338.

Dagsvik, J.K., Wennemo, T., Wetterwald, D.G. and Aaberge, R. (2002) “Potential demand for alternative fuel vehicles”, *Transportation Research B* 36, 361-384.

Davis, F. D. 1989. Perceived usefulness, perceived ease of use, and user acceptance of information technology. MIS Qutart. 13 319-339.

Ewing, G. and Sarigollu, E. (2000) “Assessing consumer preferences for clean-fuel vehicles: a discrete choice experiment”, *Journal of Public Policy and Marketing* 19, 106–118.

Gatignon H, Robertson TS. A propositional inventory for new diffusion research. J Consum Res 1985; 11(4):849–67.

Golob T.F. and Gould J. (1998) “Projecting use of Electric Vehicles from household vehicle trials”, *Transportation Research* A 32, 441–454.

Hair, J.F., William Jr., Black, C., Barry J., Anderson, R.E., (2010), *Multivariate Data Analysis*, 7/e., 2010, Pearson Prentice Hall.

Hess, S., Train, K.E., Polak, J.W. (2006) “On the use of a Modified Latin Hypercube Sampling (MLHS) method in the estimation of a Mixed Logit Model for vehicle choice”, *Transportation Research* B 40, 147-163.

Hidrue, M.K. (2010) “The Demand for Conventional and Vehicle-to-Grid Electric Vehicles: A Latent Class Random Utility Model”, PhD Dissertation UMI Number: 3440476.

Huh, Y.E., and Kim, S.H. (2008) “Do early adopters upgrade early? Role of post-adoption behaviour in the purchase of next-generation products”, *Journal of Business Research* (61), 40–46.

James M. Curran, Matthew L. Meuter, (2005) "Self-service technology adoption: comparing three technologies", Journal of Services Marketing, Vol. 19 Iss: 2, pp.103 – 113.

Kurani, K.S. and Turrentine, D.S. (1996) "Testing electric vehicle demand in hybrid households' using a reflexive survey", *Transportation Research D* 1(2), 131-150.

Lee Y, Kozar KA, Larsen KRT. The technology acceptance model: past, present, and future. Communications AIS 2003,(12):752–80.

Lieven, T., Muhlmeier, S., Henkel, S., and Waller, J.F. (2011) “Who will buy electric cars? An empirical study in Germany”, *Transportation Research D* 16, 236–243.

Masashi Kuwano, Makoto Tsukai, and Tsukasa Matsubara (2012) “Analysis on promoting factors of electric vehicles with social conformity”, *Presented at the 13th International Conference on Travel Behaviour Research*, Toronto, Canada, 15-20.

Matthing J, Per Kristensson, Anders Gustafsson, A. Parasuraman, (2006) "Developing successful technology-based services: the issue of identifying and involving innovative users", Journal of Services Marketing, Vol. 20 Iss: 5, pp.288 – 297.

Meuter, M. L., Ostrom, A. L., Bitner, M. J., & Roundtree, R. (2003). The influence of technology anxiety on consumer use and experiences with self-service technologies. *Journal of Business Research, 56*(11), 899-906. doi: 10.1016/s0148-2963(01)00276-4.

Meyers, L.S., Gamst, G., Guarino, A.J., (2006), *Applied Multivariate Research: Design and Interpretation*, Sage Publications, USA.

Mullan, J., Whitely, S., Harries, D. and Bräunl, T. (2010) "Electrification of Personal Transport in Western Australia, An Impact Study on the Rapid Introduction of Plug-in Battery Electric Vehicles and

Plug-in Hybrid-Electric Vehicles in Western Australia", EV-Report, CREST, 2010, available at: http://www.crest-au.com/docs/EV-Report-20-04-12.pdf (accessed on: May 2011).

Parasuraman A. Technology readiness index (TRI): a multiple item scale to measure readiness to embrace new technologies. J Serv Res 2000; 2(4): 307– 20.

Ratchford, M. and Barnhart, M. (2011) "Development and validation of the technology adoption propensity (TAP) index", *Journal of Business Research* (In press).

Son, M., and Han, K (2011) "Beyond the technology adoption: Technology readiness effects on post-adoption behaviour", Journal of Business Research (In press).

Venkatesh, V., & Davis, F. D. (2000). A Theoretical Extension of the Technology Acceptance Model: Four Longitudinal Field Studies. *Management Science, 46*(2), 186-204.

Voelker, J. (2009) "How Green is My Plug-In?", *IEEE Spectrum* 48-49 (6), 42- 45.

Ziegler, A. (2010) "Individual Characteristics and Stated Preferences for Alternative Energy Sources and Propulsion Technologies in Vehicles: A Discrete Choice Analysis", Economics Working Paper 10/125, available at SSRN: *http://ssrn.com/abstract=1585142*, CER-ETH, Switzerland.

Australasian Transport Research Forum 2013 Proceedings
2 - 4October 2013, Brisbane, Australia
Publication website: http://www.patrec.org/atrf.aspx

ELECTRIC VEHICLE BATTERY CHARGING BEHAVIOUR: FINDINGS FROM A DRIVER SURVEY

Fakhra Jabeen[1], Doina Olaru[1], Brett Smith[1], Thomas Braunl[2], Stuart Speidel[2]

[1]The University of Western Australia, Business School, M261, Perth, Australia

[2]The University of Western Australia, School of Electrical and Computer Engineering, Perth, Australia

Email for correspondence:20873104@student.uwa.edu.au

Abstract

This study explores drivers' charging preferences in the Western Australia Electric Vehicle trial. Drivers in this trial have experience of planning trips using plug in electric vehicles (EV). There are trade-offs between charging options in terms of cost and time. In this study each driver was given a set of four stated choice experiments; they picked their best and worst options for charging EV from each experiment. Labelled experiments contained mainly three choices: work, home and public with different values of charging cost, duration, and time of day. Drivers were given assumptions before doing the experiments, for example: that they are planning a trip for their next working day. The findings of this study give several insights into drivers' charging behaviour: drivers preferred to charge EV at home or work rather than at a public charging station; drivers having solar panels at home prefer to charge EV at home; people having travel commitments involving other family members do not like to charge EV at home but generally prefer to use a public charging station. Members of the Australian Electric Vehicle Association, one of the partners in the WA EV trial, preferred to charge at home. Drivers were in general sensitive to cost and showed a strong preference for low cost EV charging.

Key words: *Electric vehicle, stated-choice analysis, drivers' EV Charging behaviour.*

1 Introduction

A major operation with plug in electric vehicles (EV) is battery charging. Potential benefits include green impact on the environment (Ma *et al.*, 2012), home-charging (Kurani *et al.*, 1996) and low travel cost (Chan, 2007). An electric vehicle battery can be recharged by plugging into a battery charging station or unit, this battery charging operation can be done at home, which is convenient as it can be recharged overnight. Battery charging can also be done at public charging stations or specific bays provided at workplaces. Depending on battery status, requirement for a trip, or charging cost, it might be more convenient to charge at work or at a public charging station. Charging at work may not be free and usually the number of bays with charging facilities is limited. Public charging stations are provided only at certain locations and using them may require careful planning. Nevertheless, the public stations provide quick charging and are located in places of wide interest (shopping centres, hotels, transport hubs), offering additionally the privilege of a reserved/free parking bay.

In this way, there is a trade-off between the generalised cost (including the electricity price and the duration of charging) and the convenience of charging an EV. For example charging at home might be convenient, but the cost of electricity at home during on-peak hours (evening or a few hours in the morning) is different from the off-peak hours (at night or in the middle of the day, as discussed in the next section). For the purpose of this study we made a set of assumptions: drivers privately own a new electric vehicle and they have a charging facility at home or at work with a free parking bay or at a public charging station located within their daily itinerary. They are planning their next working day, the EV is the principal car at home, and their vehicle's current battery status is 30% full. The reason for these assumptions is that this study aims to determine drivers' preferences for EV battery charging with a full access to charging infrastructure at work, at a public facility, and at home. As the charging infrastructure is not well established yet in Perth, the EV drivers participating in the trial have limited options for charging. Therefore, this study explores drivers' preferences for charging at work, home or public charging stations through stated choice experiments, where drivers indicate their best and worst choice for charging an EV in hypothetical scenarios.

The next section gives more detailed information about battery charging options, with their time and cost, and home charging with solar panels; this is followed by a an introduction to the WA EV Trial, and then discussion of data and methodology is given in section 3. Section 4 presents the findings about the drivers' battery charging choices; results of this stated preference experiment provide useful insights which are further elaborated in the discussion section.

2 Electric Vehicle Battery Charging

Home charging differs from charging at work or at a public charging station both in terms of charging duration and cost. People with solar panels at home can use solar energy for EV charging during the daylight hours. Considering these variations in charging options, respondents were given a set of assumptions before starting the experiment – as presented in next section.

2.1 Battery Charging Levels: Time and Cost

Battery charging cost depends on the charging station Level (fast and expensive or slow and inexpensive), the time of the day, and the place. Level II and Level III are fast charging stations, while Level I represents a slow charging station. Accordingly, the cost of Level I charging is less than the cost of Level II, which in turn is cheaper than Level III. A Level I charging unit (usually installed at home) recharges a battery from empty to full in 6-8 hours. Level I is ideal for home use as it uses 120 V circuits providing AC power to the vehicle (National Research Council, 2013). A Level II charging station provides faster charging by using 240 V AC power, reducing charging time to 2-4 hours. Level III is also called a DC charging station because it converts AC voltage power to DC (National Research Council, 2013) and charges the EV battery at a fast speed of 10-30 mins for a full recharge. This DC charging station is ideal for public charging because of its speed.

The price of electricity is based on the time of day: peak rate (morning/late afternoon and evening) is most expensive, while off-peak (usually during the night) has the lowest rate (Table 1). The price also differs between home and business (work/public).

Table 1: Electricity Rate Synergy Home Plan effective from July 2012 (Synergy, 2012a)

Time*	Rate
Peak	45.87 cents per kWh
Off-peak	13.97 cents per kWh
Shoulder	24.44 cents per kWh
*These timings vary during summer and winter hours	

There are two power suppliers in WA: Synergy mainly supplies the metropolitan area while Horizon Power covers the rest. An overview of the on-peak and off-peak home rates is given in Table 1 as accessed from a WA power supplier website (Synergy, 2012a). These values were used in designing the stated choice experiment.

2.2 Home charging with solar panels

Solar energy systems allow their owners to generate surplus electricity during the day, thus offering zero cost daytime charging for EV at home. The photovoltaic power generation systems with benign impact on the environment (Tsoutsos *et al.*, 2005) can be ideal for EV charging, when compared to conventional energy generation sources. The cost of EV charging depends on the type of solar panel and the electricity supplier. Synergy offers a buyback price for surplus energy during the day at a fixed rate of 8.4 cents/kWh, but during night hours households have to buy at the standard rates (Synergy, 2012b). The buyback rate by Horizon Power varies across different rural areas in WA from 10 cents/kWh to 50 cents/kWh (Horizon Power, 2012).

2.3 Charging Behaviour: Previous Studies

Yilmaz, and Krein (2013) reviewed the current status of battery chargers for plug-in EV, and plug-in hybrid vehicles; no defined international standards for battery charging infrastructure exist yet. A number of studies investigated battery charging behaviour from different perspectives. For example, Peterson, and Michelek (2013) assessed the cost effectiveness of charging infrastructure, and suggest using plug in hybrid electric vehicles to reduce petrol consumption in the US. Schroeder, and Traber (2012) linked the cost of establishing the charging infrastructure with the adoption of electric vehicles. Through simple valuation methods in Germany, they found that the return on investment of a Level III charging station depends on its demand and thus relies on EV adoption at a large scale; fleet operations were suggested as one solution to increase the requirement for fast charging.

Axsen and Kurani (2012) analysed residential access to vehicle charging in order to develop an understanding of plug-in electric vehicle demand, use and energy impacts. Their findings from two different experiments were i) about half of the US population had Level I home charging access, ii) one third of the population of San Diego County had access to Level II home charging while another 20% were willing to pay the costs required for Level II installation. A higher percentage of samples having home charging access desired to have an EV as their next vehicle, compared to those who had no access. Their study did not cover all regions in the USA, however they suggested a relationship between EV charging access and EV adoption.

3 The WA EV Trial

A limited number of EVs are being driven in Perth as part of the Western Australia Electric Vehicle trial. The trial monitors the performance, benefits, infrastructure and practical implications of the EV fleet. This trial consists of eleven participant organizations, where each organization owns a number of EVs. The survey explores battery charging preferences for the drivers in the trial and how EV drivers plan their trip considering the limited range of an EV. However, these drivers experienced driving an EV that is owned by an organization and EVs are plugged-in for charging while they are parked. Though these drivers do not own an EV, for the purpose of this study drivers were given conditions before participating in the survey such as "*assume that you own an electric car*". The main objective of these assumptions was to determine preferences for charging time, charging location, and duration of charging, for EV drivers in Perth.

3.1 Conditions applying for this Study

In addition to the assumption of privately owning a new EV, drivers were asked to consider that they are planning their trip for the next working day, indicated as "tomorrow". EV drivers were given the following scenario:

- *"You own a new Electric Vehicle with a charging facility at your home; Level-I charging units are installed at home (Level I charging units are slower as compared to Level II or Level III). The cost of re-charging the EV will be added to your electricity bill, however if you have solar panels at home it will reduce the cost to zero.*
- *Suppose the requirement for your EV battery charging is from Empty (30%) to Full (100%), that is currently your battery status is 30% full.*
- *Your workplace provides free parking space for your car and you can book a bay to recharge your car if needed (Level II and Level III fast charging units are provided). There is however a price for charging at work (you are charged at the rate shown in each combination of options).*
- *A public charging station is available en route between home and work and there is a max 10 mins queuing time. However these public charging bays are located close to attractions (like coffee shop, a mall or a kid's play area). You are charged at the rate shown in each combination, and Level II and Level III fast charging units are provided.*
- *You are planning your activities and travel for tomorrow, which is a working day.*
- *Your new EV is the principal vehicle in your household."*

4 A Stated Preference Inquiry into the Choice of Charging Location

4.1 The Design of the Stated Preference Experiment

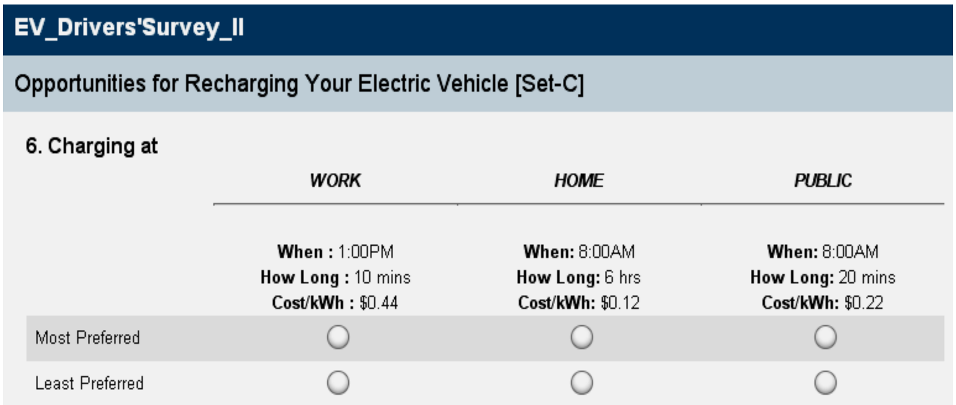
The choice tasks in the stated preference (SP) discrete choice experiment were set up with the objective of testing drivers' charging preferences. Several factors were identified as relevant to this decision: the time of day, the duration of charging, and the cost of electricity. As indicated earlier, the duration of charging depends on the type of charging station, with Level I or slow charging stations installed at home, while Level II and III stations are installed at parking bays at work or at public places.

Table 2: Attribute Levels for Experimental Design

Attribute levels for Work/Public	
Attributes	**Attribute levels**
When	8:00 AM, 1:00 PM
How Long	10 minutes, 20 minutes, 30 minutes
Cost/kWh	$0.22, $0.44
Attribute levels for Home	
Attributes	**Attribute levels**
When	8:00 AM, 1:00 PM, 9:00 PM
How Long	6 hours, 7hours, 8hours
Cost/kWh	$0.12, $0.30

The attribute levels are shown in Table 2. An orthogonal experimental design was generated using statistical software package (SPSS). Choice combinations deemed infeasible or with dominance were removed. A set of 4 scenarios was given to each respondent in one treatment with each scenario containing three options/alternatives. In designing this experiment, five different sets were generated, each containing four scenarios with three options. These five blocks (A, B, C, D, E) were randomised in that each respondent was randomly given one or more blocks to complete. In this way each respondent provided answers for at least four scenarios.

Table 3: An Example of a Choice Scenario



EV_Drivers'Survey_II

Opportunities for Recharging Your Electric Vehicle [Set-C]

6. Charging at

	WORK	*HOME*	*PUBLIC*
	When : 1:00PM **How Long :** 10 mins **Cost/kWh :** $0.44	**When:** 8:00AM **How Long:** 6 hrs **Cost/kWh:** $0.12	**When:** 8:00AM **How Long:** 20 mins **Cost/kWh:** $0.22
Most Preferred	○	○	○
Least Preferred	○	○	○

An example of a scenario with labelled alternatives is given in Table 3. Respondents were asked to indicate the most preferred and the least preferred options. There are advantages in allowing the respondent to choose best/worst (Finn and Louviere, 1992) options, primarily more information being obtained from one scenario. For example, with a set of three alternatives a complete ranking of four scenarios provides 8 choice situations, even though the respondent looks at only four scenarios.

4.2 Information about respondents

An invitation to participate in the survey was sent out on 24 Sep 2012, to the eleven participant organisations in the WA EV Trial. Given that the Australian Electric Vehicle Association (AEVA) is one of the partner organisations in WA EV Trial, a large number of respondents in this survey were from AEVA (Table 4).

Table 4: WA EV Trial Sample

Organization	Out of Total 67	Out of the 54 Completed Surveys
AEVA	54	32
Non AEVA	23	22

A total of 67 respondents participated in the survey with 54 complete sets of responses. Many of these drivers had participated in an earlier survey of the acceptability of electric vehicles (Jabeen *et al* 2012).This second driver survey included two sections: 1) background questions and 2) scenarios for EV charging at work/home/public points. A summary of the sample's socio-demographic characteristics is given in Table 5.

Table 5: Sample Information

Variable	%	Count (Total=54)
Gender		
Male	79.6	43
Female	20.4	11
Age		
<29	11.1	6
30-49	48.1	26
50-59	13.0	7
60+	27.8	15
What is your highest level of education?		
Year 12	13.0	7
College/Professional qualification	20.4	11
University Bachelor Degree	40.7	22
Masters or PhD	25.9	14
Do you usually have travel commitments involving other family members (e.g., pick-up/drop-off)?		
Yes	44.4	24
No	55.6	30
Do you have solar panels on your roof top?		
Yes	44.4	24
No	55.6	30

The sample was dominated by male respondents (79.6%), reflecting closely the population of EV users in Perth. Approximately half of the respondents (48.1%) were in the 30-49 years age group, 27.8% were above 60 years of age, and only 11.1% were young (<29 years). Thirty six (66.6%) of the respondents had university education. In addition to these socio-demographics, respondents were also asked about their travel commitments - involving other family members - and about having solar panels at home. From the data set it was observed that the majority (61%) of AEVA members had solar panels at home.

5 Drivers' Battery Charging Behaviour

Each respondent indicated their best and worst choices for charging at a particular place in each choice set. For the purpose of analysis, the Econometric Software NLOGIT 5.0 was used. By using a most preferred-least preferred design, an exploded choice set was generated, with multiple observations from one respondent. After data cleaning a total of 900 observations was obtained from 54 complete sets of responses. Each respondent indicated their best and worst option this is the reason that a large number of observations were achieved.

5.1 Multinomial Logit Model Estimation

The analysis of drivers' preferences for charging EV, at work, home, or public, started with the simplest discrete choice model – the multinomial logit (MNL).This model remains the starting point for empirical investigations of data such as preliminary data checks before applying advanced discrete choice models (Louviere *et al.*, 2000).

MNL Model Specifications: The systematic component of the utility functions tested for this MNL model with the model fit are given below (Table 6) and the parameter estimates obtained from three MNL models are given in Table 7. The model was also tested with variables reflecting personal characteristics (age, gender, and income), but they were not significant.

Table 6: MNL Model Specifications

$$V_{home} = \beta_{morning}X_1 + \beta_{night}X_2 + \beta_{howlong}X_3 + \beta_{cost}X_4 + \beta_{solar}X_5$$

$$V_{work} = \alpha_{work} + \beta_{morning}X_1 + \beta_{lunch}X_2 + \beta_{howlong}X_3 + \beta_{cost}X_4 + \beta_{AEVA}X_5$$

$$V_{Public} = \alpha_{Public} + \beta_{morning}X_1 + \beta_{lunch}X_2 + \beta_{howlong}X_3 + \beta_{cost}X_4 + \beta_{fam\_com}X_5$$

Model fit: The log likelihood function of the MNL model with the best fit, model M3 gives log-likelihood (LL) value= -627.81, and Chi-squared value with 8 degrees of freedom equals 669.79 (Table 7). With constants only, LL = -749.49.Table 7 also shows the pseudo-R^2 calculated for each model using equation (1).

$$\boldsymbol{\rho^2 = 1 - \frac{LL_{Estimated\ Model}}{LL_{Base\ Model}}} \tag{1}$$

Parameter estimates: The first model M1, tests the preferences for EV charging at a place, time of day, cost, and duration of charging. The alternative specific constants with a negative sign for work and public in model M1 and model M2 indicate that drivers showed a preference to charge their EV at home or at work instead of public charging stations (Table 7).

Table 7: Multinomial logit model estimates

	M 1		M2		M 3	
	Beta	z	Beta	z	Beta	z
Charging at public	-3.37***	-5.24	-3.52***	-5.16	-0.50	-0.60
Charging at work#	-2.12***	-3.33	-1.39**	-2.07	1.7**	2.04
Time of Day	0.43***	5.18	0.48***	5.53		
MORNING	Time of day				0.09	0.39
LUNCH TIME					0.13	0.49
NIGHT					1.96***	7.38
Cost ($)	-4.35***	-7.76	-4.79***	-8.17	-3.75***	-6.13
HowLong (Duration in Mins)	-0.007***	-4.75	-0.008***	-5.11	-0.001	-0.72
Solar Panels At Home			0.97***	5.48	1.01***	5.45
Family Commitments wrt Home Charging			0.32*	1.81	0.34*	1.88
AEVA Members charging at work			-1.06***	-5.89	-1.17***	-6.20
Number of parameters (K)	5		8		10	
Log likelihood	-695.207		-655.168		-627.811	
AIC	1400.4		1326.3		1275.5	
ρ^2 (*Mc Fadden*)	0.07		0.12		0.16	
Log likelihood With constants only	-749.489					

#Home is reference; *****, **, * indicate Significance at 1%, 5%, and 10% level respectively**

The time of day variable was coded in ordinal form to represent morning, lunch time, and night hours as -1, 0, and 1 respectively. Positive parameters for this variable in M1, and M2 indicated that drivers preferred to charge their EV during night hours. In M3, the time of day variable was coded using dummy variables; their respective parameter estimates clearly indicate higher preference for charging at night (β=1.96, z=7.38), and lower preference for charging during the day times. Drivers are sensitive to the time taken to charge EV, and even more sensitive about EV charging cost, as shown by the parameter values in M2 (β=-4.79,z= -8.17).

Covariates: Drivers having solar panels at home preferred to charge their EV at home; this is indicated by significant parameter estimates in M2 and M3 for the solar panels at home covariate in Table 7. This preference for charging EV at home might be due to the savings in cost for charging EV using solar panels, and/or because of the convenience of charging EV at home. As mentioned above, almost 61% of AEVA members who participated in this survey had solar panels at home; thus there was overlap between these two groups, that is, AEVA members showing a strong preference for charging at home and drivers having solar panels at home. AEVA members preferred not to charge their EV at work, with negative coefficients in both M2 and M3. Drivers having travel commitments involving other family members showed a preference for charging their EV at a public charging station during the day (10% significance level).

5.2 Random Parameters Logit Model Estimation

Random parameters or mixed logit model (RPL/ML) is an advanced model used for exploring the behavioural output, elasticity of choice, and valuation of attributes (Louviere *et al.*, 2000).Revelt and Train (1998) suggested that the RPL interpretation is useful when considering models with repeated choice, RPL*'...allows efficient estimation when there are repeated choices by the same customer (*decision maker*)*". Although the ML model is also termed the error components model (Hensher, and Greene, 2003), due to the multiple observations/respondents, i.e. panel data, we used the random parameters logit model along with error component model (ECM) specifications. Standard Halton sequence draws (SHS) were used in drawing random parameters because SHS is an intelligent draw method that can obtain good results with a small fraction of the total number of draws required by other methods, and is designed to sample the entire parameter space (Baht, 2001;Train, 2003).
A total of 459 experiment situations were used in this analysis. There were 18 instances where respondents indicated only their most preferred choice but did not answer their least preferred option, which resulted in a total of 900 valid observations.

Model Structure: Assuming that each sampled driver q is given J=3 alternatives, in each of choice situation, the number of choice situations given to each respondent was variable (T=4, 8, 12, 16, or 20). A utility expression of general form for a discrete choice model is given as following:

$$\begin{aligned} U_{jtq} &= \sum_{k=1}^{K} \beta_{qk} x_{jtqk} + \varepsilon_{jtq} \\ &= \beta'_q x_{jtq} + \varepsilon_{jtq} \end{aligned} \tag{2}$$

where, j= 1,.., 3 alternatives,
t= 4, 8, 12, 16, or 20 choice situations,
q=1,....., 54 respondents
x_{jtqk} is the full vector of explanatory variables including attributes such as time of day, duration, and cost of charging against each alternative, and choice task itself in choice situation *t*.
In this experiment more than one observation from each respondent was collected for T choice situations in time-period i = {i1, ...iT}. The probability conditional on β that a respondent makes this sequence of choices is the product of logit formulas (Train, 2003) given in equation (3).

$$L_{qi}(\beta) = \prod_{t=1}^{T} \left[\frac{e^{\beta'_q x_{qi_t t}}}{\sum_j e^{\beta'_q x_{qjt}}} \right] \tag{3}$$

As mentioned above, each driver in this survey was given a different number of choice situations; thus analysed using the RPL/ECM model with repeated choices, the unconditional probability is the integral of this product over all values of β, as given below:

$$P_{qi} = \int L_{qi}(\beta) f(\beta) d\beta \tag{4}$$

Table 8: Mixed logit/Error Component Model Parameter Estimates

Non-random parameters in utility functions		
	Beta	**z**
Charging at public[#]	-0.06	-0.04
Long Duration (Hours)	-0.001	-0.32
Short Duration (Mins)	-0.04	-1.6
NIGHT	3.67***	12.95
Random parameters in utility functions		
Cost for Charging at home/work	-9.83***	-11.06
Cost for Charging at public stations	-7.33***	-4.58
Charging at work	2.6*	1.67
Heterogeneity in mean variable: parameter		
Work: Solar Panels	-1.75**	-2.27
Work: Family Commitments	1.3	1.6
Work: AEVA Members	-1.9***	-2.6
Cost: Solar Panels	-8.05***	-3.17
Cost: Family Commitments	6.06**	2.56
Cost: AEVA Members	-3.17	-1.41
Derived standard deviations of parameter distributions		
Cost for Charging at home/work	5.9***	11.06
Cost for Charging a public stations	4.4***	4.58
Charging at work	3.6***	4.74
Error Components		
Work, Public	2.49***	5.23
Model Fit		
Number of parameters (K)	16	
Log likelihood	-467.05	
AIC	966.1	
ρ^2	0.37	
Adjusted ρ^2	0.527	

[#]***Home is reference*** *****, **, * indicate Significance at 1%, 5%, and 10% level respectively**

The specified random parameters in the RPL/ECM model were for charging at work, and charging costs. Adding a random parameter for charging time caused an insignificant improvement in overall fit, thus it was kept as a non-random parameter (Table 8).

In this model specification, Halton sequence draws were used to estimate random parameters with two normal distributions, and one triangular distribution. The normal distributions were used for the cost of charging at home/work, and the cost of charging at public stations, and the one triangular distribution was used for the alternative specific for charging at work. SHS is an efficient drawing method that reduces the chance of drawing parameters from a particular part of the distribution (Baht, 2001); thus to give good results 100 intelligent Halton draws for β were used. Other parameters not specified as random were interpreted similarly to the parameter estimates in the MNL. The parameter estimates using the RPL/ECM model are given in Table 8.

Model fit: With the same 900 observations from 54 respondents, the LL value of the RPL/ECM model has improved on the MNL models in Table 7 with log-likelihood = -467.05 (as given in

Table 8). The Chi-squared value with 16 degrees of freedom for this model equals 1,043.38. Using equation (1), the pseudo R^2 for this model is 0.37 which is approximately equivalent to $R^2 \approx 0.71$ for a linear regression model (Hensher *et al*., 2005; p.338).

Preference Heterogeneity: The random parameters logit model allows preference heterogeneity around the means of random variables that can be used to test interaction effects. Statistically significant parameter estimates for *derived standard deviations of random parameters* indicate that there is *heterogeneity in the parameter estimates over the sampled population around the mean parameter estimate* (Hensher *et al*., 2005; p.633). Variables that were covariates in the MNL model earlier (Table 7) are explored here for their interaction effects. Using the RPL model the preference for charging at home while having solar panels at home, and having travel commitments with family members were tested for interactions. This provided useful insights into the drivers' charging behaviour and their preferences for charging at home, and their preferences with respect to charging cost. The results in Table 8 indicate the following:

- In general drivers had a preference for charging their EV during night hours, and they were sensitive to cost and duration of charging.
- Drivers who were AEVA members did not favour charging at work but were marginally sensitive to charging cost at public charging stations.
- Similarly, drivers having solar panel at home did not like to charge EV at work, and they also showed a negative reaction to the cost of charging at public stations.
- Drivers having travel commitments with family were prepared to pay a high cost for EV charging. This behaviour indicates the importance of charging infrastructure.

5.3 Charging Price and Duration Elastiticities

Results from the RPL/ECM model indicated the sensitivity to duration and cost of charging. Choice elasticity with respect to charging cost and with respect to duration of charging are presented in Table 9 and Table 10 respectively. The own elasticity for charging at work of -0.57 indicates that a 10% increase in the cost of charging at work results in a 5.7% decrease in the preference for charging at work, all else being equal. The own elasticities for home, and public are -0.40, and -0.52 respectively. As an example of an (off-diagonal) cross-elasticity, a 10% increase in the cost of charging at home would result in a3.8% increase in the preference for charging at public charging stations, ceteris paribus (Table 9). These values for choice elasticity with respect to charging cost indicate that all three charging alternatives are fairly close substitutes. This is further supported by the beta weights for (*Work, Public*) error components where work and public showed strong correlation values in Table 8.

Table 9: Choice Elasticity with respect to the Charging Cost Attribute

Preference for	Cost at Work	Cost at Home	Cost at Public
Charging at Work	**- 0.569**	0.148	0.208
Charging at Home	0.175	**-0.401**	0.182
Charging at Public	0.464	0.380	**-0.517**

The direct charging duration elasticity for charging at public charging stations of -0.2 indicates that 10% increase in public charging duration will result in 2% decrease in the preference for charging at public charging stations all else being unchanged (Table 10). For cross elasticities, a 10% increase in charging duration at public stations results in less than a 1% increase in the preference for charging at home or for charging at work, all else being equal.

Table 10: Choice Elasticity for Charging with respect to Charging Duration at Public Charging Stations

Preference for	With respect to charging duration at public stations
Work	0.078
Home	0.073
Public	**- 0.200**

5.4 Willingness to Pay (WTP) for reducing Charging Duration

WTP measures were calculated in a similar manner as for MNL except that through the RPL model, a WTP Matrix containing the willingness to pay measure for each observation was calculated *as a ratio of the coefficient of charging duration in minutes to the coefficient for charging cost in dollars*.

$$\boldsymbol{WTP_q = \left(\frac{\beta_{time_q}}{\beta_{cost_q}}\right) \times 24} \tag{5}$$

The WTP measure for each respondent *q*, was calculated in the WTP Matrix on a kWh basis. It takes 24kWh to charge an EV from zero to full (National Research Council, 2013). Hence, to get the cost for a full charge this value was multiplied by 24. By taking an average of the resulting values, drivers in the WA EV trial were willing to pay $1.17 extra for a 10 minute reduction in charging time. This value, though small, is comparable to the existing cost of charging electric vehicles. The willingness to pay measures for charging convenience was also calculated in a similar manner, but it did not reveal any additional meaningful results.

6 Discussion and Future Research

Home-charging remains one of the advantages of EV as drivers had a preference for the convenience of charging overnight or during the day at home. Drivers having solar panels preferred to charge at home, this preference being explained by the saving in cost and also the convenience. Average daily travel distance requirements of 25-30 kms in Australia (*BITRE*, 2010) are supported by a comment from one of the drivers in this survey: "..... *4 months ago we purchased the all-electric car Nissan LEAF. So far this has nearly always been solar charged at home........*", showing that current EV range is sufficient for household travel requirements in this part of Australia. An argument for daytime home charging is that the cost of overnight charging EV while having solar panels at home is determined by the buy-back rate provided by the power supplier. As mentioned earlier Synergy offers 8.4 cents/kWh, while Horizon Power offers10 cents/kWh to 50 cents/kWh in different rural areas/suburbs of Western Australia (WA). For this reason households may experience various costs for charging at night.

AEVA members preferred not to charge their EV at work as many had solar panels at home. In the RPL model AEVA members were not sensitive to price at public stations, and their preference for home charging reflects their enthusiasm for using renewable energy. Another factor is convenience, indicated by drivers' comments, as exemplified here: "*I would insist on charging at home no matter the cost.*"

Drivers having travel commitments involving other family members showed a stronger preference for charging EV at public stations. This could be due to the requirement for their long trip, involving a pickup/drop of a family member or some household chores. One of the respondents who had travel commitments involving other family members made a comment that: "*Public charging facilities, e.g. at shopping centres and in city centre would definitely be useful.*" This indicates that it is convenient for people to plug-in their EV and effectively use the charging time for other activities, therefore public charging stations installed near places of interest are appealing.

Charging at public charging stations is different from charging at home or at work. The convenience of overnight or during the day differentiates home-charging from public charging. For charging at work, the convenient location, less effort and convenient timing makes it different from charging at public stations. The cross elasticities with respect to charging duration in Table 10of about 0.07 indicate that the time to charge at a public station has a small impact on the probability of charging at home or work. It is a matter of trip length that leads drivers to charge at public charging stations during the day. In general, drivers were sensitive to charging cost, but convenience was also important, as pointed out by one of respondents: "*I think if your battery capacity permits, you will charge wherever it is both cheap and convenient. If not one, you will go for the other.*"

The main aim of this experiment was to test WA EV Trial drivers' preferences for EV charging. The study has several limitations, with *i)* reduced number of respondents and *ii)* lack of a charging infrastructure being the most evident. At the time when this study was conducted the charging stations in WA were in their infancy but the drivers in the trial had ample experience of EV charging.

7 Conclusion

This paper explores the drivers' preferences for charging at work, at home, and at public charging station. With ~~a~~ limited availability of charging infrastructure, stated choice experiments were used to analyse driver's charging preferences. Advanced discrete choice models were used to analyse panel data. Main observations from this study are that drivers' in most instances preferred to charge EV at home/work, and they were sensitive to charging cost and duration. Among the drivers in the WA EV trial, people having solar panel at home were generally enthusiasts who preferred to use the renewable energy to charge their EV at home.

Overall drivers were sensitive to charging cost, and duration, but people having travel commitments with family were prepared to take the time required to charge at public charging stations.

8 References

Axsen, J., & Kurani, K. S. (2012) "Who can recharge a plug-in electric vehicle at home?" *Transportation Research Part D: Transport and Environment*, 17(5), 349-353.

Baht C.R. (2001) "Quasi-random maximum likelihood estimation of the mixed multinomial logit model", *Transportation Research B,* 35(7), 677-695.

Bureau of Infrastructure, Transport and Regional Economics (BITRE) (2010) *Population growth, jobs growth and commuting flows in Perth*, accessed on 7th Nov. 2012, available at: http://www.bitre.gov.au/publications/2010/files/report_119.pdf, Canberra ACT.

Chan C. C. (2007) "The state of the art of electric, hybrid and fuel cell vehicles," *Proceedings of the IEEE*, 95(4), 704–718.

Finn, A., & Louviere, J. J (1992) “Determining the Appropriate Response to Evidence of Public Concern: The Case of Food Safety”. *Journal of Public Policy & Marketing*, 11(1), 12-25.

Hensher DA, Rose J, & Greene WH. (2005) *Applied Choice Analysis: A Primer*. Cambridge University Press: Cambridge.

Hensher, D., & Greene, W. (2003) “The Mixed Logit model: The state of practice”, *Transportation*, 30, 133-176.

Horizon Power. (2012) “Renewable EnergyBuyback Pricelist”, http://www.horizonpower.com.au/documents/RENEWABLE_ENERGY_BUYBACK_PRICE_LIST__EFFECTIVE_FROM_1_JULY_20123503450.PDF, accessed on 19th March 2013.

Jabeen, F., Olaru, D., Smith, B., Braunl, T., Speidel S. (2012) “Acceptability of electric vehicles: findings from a driver survey”, *Proceedings of the ATRF* (Australasian Transport Research Forum), September 2012, Perth, Australia.

Kurani, K.S., Turrentine, T.S, and Sperling, D. (1996) "Testing electric vehicle demand in hybrid households' using a reflexive survey", *Transportation Research D* 1, 131-150.

Louviere, J.J. and Woodworth, G.G. (1990) *“Best-worst scaling: a model for largest difference judgments”*, working paper, Faculty of Business, University of Alberta, Edmonton.

Louviere, J.J., D.A. Hensher, D.A. and Swait, J.D. (2000) *Stated Choice Methods Analysis and Application*, Cambridge University Press, USA.

Ma, H., Felix, B., Tait, N., Xavier, R.P., and Andrew, H. (2012) “A new comparison between the life cycle greenhouse gas emissions of battery electric vehicles and internal combustion vehicles”, *Energy Policy* 44, 160-173.

National Research Council. (2013) *Transitions to Alternative Vehicles and Fuels.* Washington, DC: The National Academies Press.

Peterson, S. B., &Michalek, J. J. (2013) “Cost-effectiveness of plug-in hybrid electric vehicle battery capacity and charging infrastructure investment for reducing US gasoline consumption”, *Energy Policy*, 52, 429–438.

Revelt, D., & Train, K. (1998) Mixed logit with repeated choices: households' choices of appliance efficiency level. *Review of economics and statistics, 80(4)*, 647-657.

Schroeder, A., &Traber, T. (2012) “The economics of fast charging infrastructure for electric vehicles”, *Energy Policy,* 43, 136-144.

Synergy.(2012a) “Standard Electricity Prices and Charges South West Interconnected System”, accessed on 17th Sep 2012, available athttp://www.synergy.net.au/docs/Standard_Electricity_Prices_Charges_brochure_MSF.pdf.

Synergy. (2012b) “Renewable EnergyBuyback Scheme and Net Feed in Tariff Price Schedule”, available at: https://www.synergy.net.au/docs/SYNB1058_REBS_Price_Shedule_DL_web.pdf, accessed on 17th Sep 2012.

Train, K. (2003) *Discrete choice methods with simulation*: Cambridge University Press, UK.

Tsoutsos, T., Frantzeskaki, N., & Gekas, V. (2005) “Environmental impacts from the solar energy technologies”, *Energy Policy*, 33, 289-296.

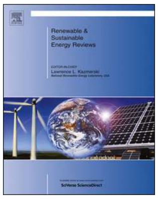
Yilmaz, M., &Krein, P. (2013) “Review of Battery Charger Topologies, Charging Power Levels and Infrastructure for Plug-in Electric and Hybrid Vehicles”, *IEEE TRANSACTIONS ON POWER ELECTRONICS,* 28(5), 2151-2169.

Renewable and Sustainable Energy Reviews 40 (2014) 97–110

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



Driving and charging patterns of electric vehicles for energy usage

Stuart Speidel [1], Thomas Bräunl *,[1]

REV Project The University of Western Australia School of Electrical, Electronic and Computer Engineering, 35 Stirling Highway Crawley, WA 6009, Australia

ARTICLE INFO

Article history:
Received 7 October 2013
Received in revised form
21 May 2014
Accepted 19 July 2014

Keywords:
Electric vehicle charging
Electricity Grid
Home charging
Pool vehicles

ABSTRACT

This paper presents findings from the Western Australian Electric Vehicle Trial (2010–2012) and the ongoing Electric vehicle (EV) charging research network in Perth. The University of Western Australia is collecting the data from eleven locally converted EVs and 23 charging stations. The data confirms most charging is conducted at business and home locations (55%), while charging stations were only used for 33% of charging events. The EV charging power over time-of-day and aggregated over all charging stations closely resembles a solar PV curve, which means that EV charging stations can ideally be offset by solar PV. Another important finding is that EVs spend significantly more time at a charging station than what is technically required for the charging process. Also on average, EVs have more than 50% battery charge remaining when they plug in. This tells us parking spaces are in higher demand than Level-2 charging facilities.

Contents

---

* Corresponding author.
E-mail address: thomas.braunl@uwa.edu.au (T. Bräunl).
URL: http://www.therevproject.com (T. Bräunl).

[1] Tel.: +618 6488 3897; fax: +618 6488 1168.

http://dx.doi.org/10.1016/j.rser.2014.07.177
1364-0321/

1. Introduction

Rising fuel costs, growing public awareness and concern over environmental issues such as urban air quality and global warming, combined with higher-performance batteries mean that electric vehicles are emerging as an attractive alternative to internal combustion engine (ICE) petrol/diesel vehicles. Automobile manufacturers such as Nissan, Mitsubishi, BMW, Renault, Ford and Tesla are taking advantage of the emerging marketplace by releasing their own commercial electric vehicles. EVs can be home charged, so they do not require an immediate charging infrastructure, however it can be argued that EV take-up rates do depend on the availability of an adequate EV charging infrastructure. Modern charging stations can adapt their energy usage to grid load requirements by reducing or increasing charge current. This also allows charging stations to maximise renewable energy usage, e.g. through charging with higher currents during sunshine hours or during times of high wind speeds and low energy demand at night. Careful analysis, planning and management will be needed to determine the necessity, reduce the costs of, and optimise placement and operation of this charging infrastructure.

In this paper we analyse and discuss the data that has been collected from eleven EVs and 23 charging stations during the WA Electric Vehicle Trial (January 2010–December 2012), the first electric vehicle trial conducted in Australia (Fig. 1). The data collected shows for each charging event the energy used and the start and stop time of charging. This can be used to determine a possible renewable energy offset and to predict the impact of a future larger fleet of EVs on the power distribution network. All trial EVs were equipped with black box data loggers, so we received charging events not only from charging stations, but also from all other locations where a car has been plugged in, most notably home and office locations. From this we can derive statistics on the usage of the charging stations, including the charging probability, the charging location types and driver behaviours. These results supply accurate and detailed EV driving patterns that are useful for EV charging grid modeling [1].

The WA Electric Vehicle Trial was led and coordinated by local company CO2Smart in cooperation with the Renewable Energy Vehicle Project (REV) at The University of Western Australia (UWA). Some preliminary trial results from this trial have been published in Refs. [32,2].

The majority of EV charging stations were installed as part of an ARC Linkage Project at UWA, while WA Electric Vehicle Trial participants funded the remaining stations. In total there are 23 charging stations installed at twelve different locations (see Fig. 2).

EVs have zero emissions from driving if the electricity supplied is generated from renewable resources. In Australia, the concern about greenhouse gas (GHG) emissions from electricity production has seen a greater desire for energy efficiency and alternative, renewable energy resources [3]. 91.8% of the electricity supplied in Australia is generated from fossil fuels, with the remainder being generated from bioenergy, wind, hydroelectricity and solar photovoltaic (PV) systems [4]. The electricity mix used to charge an EV has a huge impact on its total GHG emissions during the vehicle's lifetime [5]. The domination of fossil fuels in the Australian market significantly increases GHG emissions from the EVs and encourages a focus on maximising the utilisation of renewable energy sources.

To maximise the usage of renewable energy in charging, strategies such as smart charging are being developed [6]. Smart charging is defined as either the EV, the charging station, or the network operator controlling when an EV will charge and how much power the EV should draw at a given time. For an intermittent source of energy such as wind power, smart charging can improve the renewable energy utilisation and therefore reduce GHG emissions [7,8]. Smart charging can also maximise the usage of PV systems, charging the vehicle when the PV system is generating excess power [9]. Smart charging has the downside of additional cost and complexity and requires communication between multiple stakeholders including the energy generator and the EV [10]. However, smart charging offers a huge opportunity to avoid grid overload by deferring charging operations for a large number of EVs [11]. Such systems need to be regulated and standardized to increase safety and performance [12].

Li and Wang [1] provide an overview of modelling plug in hybrid EVs (PHEVs) impact on the distribution grid, suggesting driving patterns, charging characteristics, charge timing, and vehicle penetration are the key factors behind EV energy usage. Some studies simulate EV charging patterns from vehicle fleet patterns [13–15] and will be used for comparison with our results collected. Ashtari, Bibeau [16] use vehicle tracking devices in 76 petrol vehicles and a stochastic method to determine hypothetical charging patterns, creating a load graph by hour. Their results show a charging load profile that has a peak at night when the vehicles are returned home.

Vehicle-to-grid technologies allow the EV to return stored energy into the electricity grid [17]. Research from our group has shown the vehicle-to-grid technologies are not viable due to excessive battery wear and high infrastructural costs [18]. The lifetime of EV batteries is determined by the total number of charge/discharge cycles, so vehicle-to-grid technologies will effectively reduce the life of an EV battery by half [19] and manufacturers such as BMW have opted against using vehicle-to-grid technologies because of this [20]. The charging station infrastructure and the EVs in this trial were not enabled for vehicle-to-grid technologies for the same reasons.

EVs are likely to have a slow uptake [21,22] and it is unlikely EV charging will create significant problems for the WA electrical grid over the next 10 years [23]. Simulation models done for Victoria,

Fig. 1. Electric Ford Focus fleet.

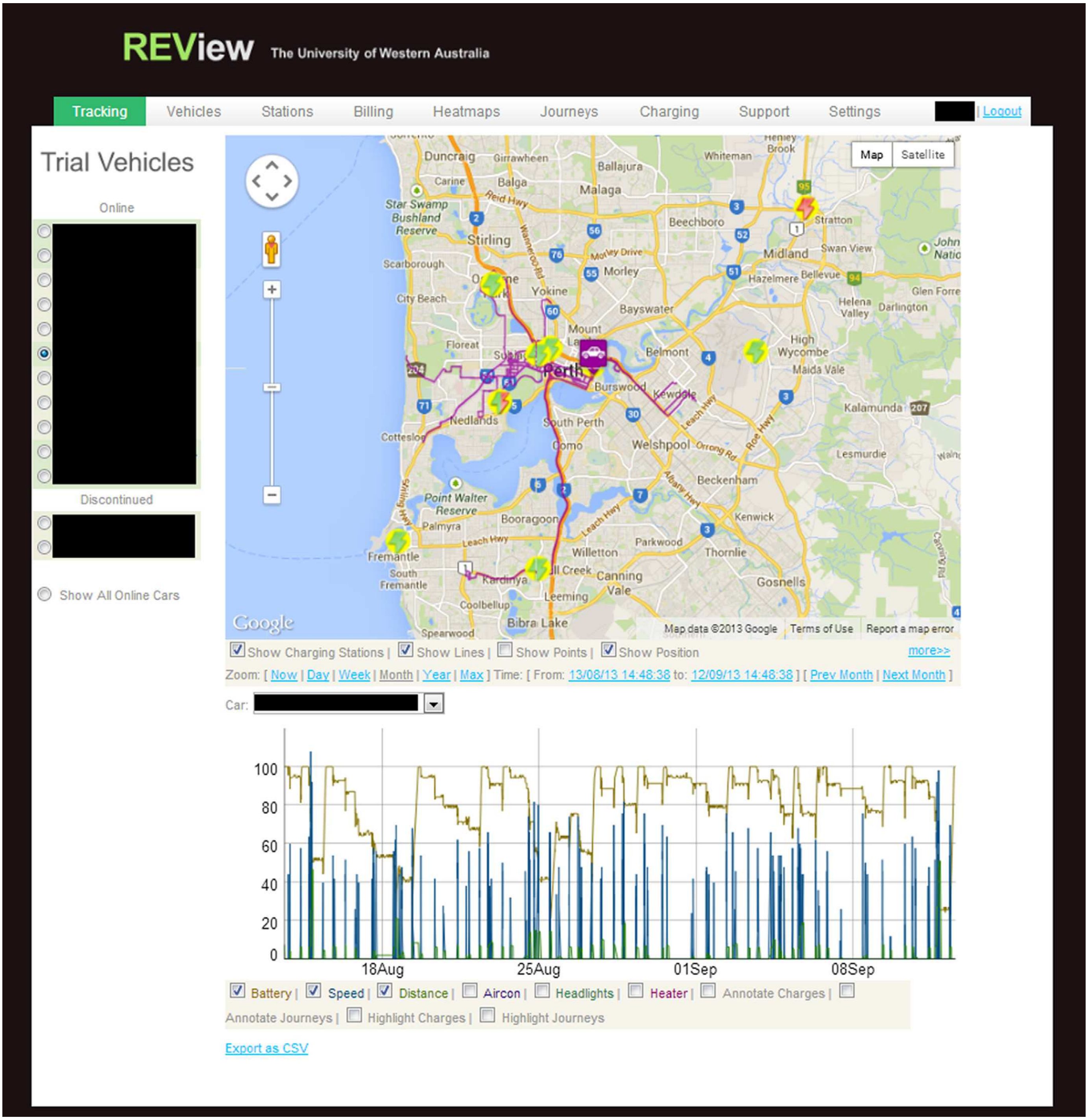


Fig. 2. Electric vehicle charging stations installed in Western Australia as part of The University of Western Australia Charging Station trial, shown inside the web software for the EV Trial users.

Australia, predict that a high uptake of EVs of around 15–20% of total non-commercial private motor vehicles by 2030 would increase electricity consumption by only 5% [24]. Even in the unlikely event that there is a large uptake of EVs, the impact on the grid will not be a problem in the short to medium term [22].

2. Methodology

2.1. EV conversion

A Ford Focus sedan (model year 2010) was chosen as the base vehicle for the WA Electric Vehicle Trial. Eleven vehicles, one for each trial participant, have been purchased and converted to EVs by local company EV Works. The cost to convert the vehicle from petrol to electric was AUD 30,000 (AUD 20,000 in parts and AUD 10,000 in labour) while the original petrol vehicle cost AUD 20,000.

The electric Ford Focus used 45 Thunder Sky Lithium Ion Phosphate batteries in series, each providing 160 Ah at 3.2 V for a vehicle voltage of 144 V and total battery capacity of 23 kWh. This gave the vehicles a maximum driving range of 131 km (road tested) and 143 km (dynamometer tested), respectively, at the date of conversion. The vehicles used a Netgain Impulse 9 motor with an EVNetics Soliton-1 motor controller which was electronically limited to 480 A, 69 kW power output. An electric vacuum pump was fitted for the brake assist and the air conditioning unit was powered by either a separate dedicated electric motor or a belt connection to the vehicle's drive motor.

All of the original 12 V electronics were retained during conversion with an Iota DLS-55 DC-DC converter to charge the 12 V battery from the main battery pack. This included the vehicle's onboard computer, which was required to drive the dashboard instruments, indicators, etc.

The electric Ford Focus was fitted with a Protech 5 kW dual mode battery charger. The charger allows both single-phase charging (low or high current) and three-phase charging. The charger has two modes, one for charging at a three-phase outlet at 4.8 kW and another for a single-phase outlet at 1.8 kW. The vehicle's charger is able to charge the car from empty to full in about four hours at 4.8 kW and about eleven hours at 1.8 kW.

EV chargers draw a consistent and high current for a long time. When the vehicle battery is full, the charger switches to a maintain-charge mode, which maintains the batteries at full charge. The trial EV chargers use on average 120 W to maintain the batteries at full charge.

The vehicle transmission was retained from the original vehicle. Each organisation had a choice of a manual gearbox with or without a clutch or an automatic. Most participants opted for the manual gearbox with a clutch, only the first prototype car was built as a clutchless manual and only one automatic version was built. Both had some significant disadvantages. The clutchless manual has been a standard for many EV conversions and is legally considered an ‘automatic’ by Australian law. This fact makes it attractive as a pool car for larger organisations, as a significant number of drivers in Australia have automatic-only driver licences. Unfortunately, performing a gear change while driving is required when changing from city driving to freeway driving and back and it is not trivial, especially for inexperienced drivers to change gears without a clutch.

The problem with the automatic gearbox conversions was that at the time of conversion it was not possible to modify the car computer settings to enable smooth gear changes for the electric motor. When taking off, the vehicle would shift quickly between first and second gear as the electric motor quickly gained speed, causing the vehicle to jerk. Therefore the automatic gearbox was locked in third gear when in drive mode. For an automatic transmission the engine is required to be idling at all times, so the electric motors in the trial automatic vehicles would idle at 700 rpm. The locked gear position and the constant idling reduced the road-tested range of the automatic vehicle to around 100 km.

The average EV power consumption with a manual gearbox measured at 197 Wh/km, or 242 Wh/km when including charging losses.

2.2. Charging stations and data logging

Level-2 charging stations from manufacturer Elektromotive had been selected for the EV trial and the EV charging research project. Each charging outlet cost AUD3000 to purchase plus an additional AUD1000 for wall mounting or AUD2000 for ground installation. In the absence of an Australian standard, charging stations were purchased complying with the European standard IEC 62196 Type-2 (Mennekes) connectors [25], which unlike the US/Japan standard Type-1 (J1772) does support three-phase charging. Since Australia like Europe does have a three-phase power grid, this should be the obvious choice. Since cables are not a part of Type-2 charging station itself, it can charge both EV types (Type-1 or Type-2) with a matching charge cable.

Each charging station is equipped with a data logger and a GSM modem to transmit charging data to a central host system. On the vehicle side, we have installed GPS-based black box data loggers, which are also equipped with GSM data loggers to transmit vehicle tracking data to our central server. To measure the energy usage of the vehicles, the GPS tracking devices have in addition five digital inputs and one analogue input, which were used to measure the status of the car's air conditioning, heater, headlights, charging, ignition as well as the analogue battery charge level. GPS positions and line inputs are uploaded onto the UWA server either at every minute or at every ten metres, whichever comes first (see Fig. 15). During the duration of the trial 5,640,987 data sets were entered into the database from the eleven EVs (see Fig. 13).

The data is processed using a Python batch script and displayed to the trial participants via a web portal interface (see Fig. 2) that displays telemetry data, driving and charging statistical heat maps for each one of the vehicles. The data processing generates journey, charge and parking events. From the collected GPS data a heat map displaying the EV charging is shown in Fig. 5, EV parking in Fig. 6, and EV movement in Fig. 14.

2.3. Charging events and data interpretation

EV driving events are divided into ‘journey’ segments by the tracking device. Each journey has a start time and location, an end time and location, a total travel distance, air conditioning usage time, heater usage time, headlight usage time and the estimated battery level. A journey starts when the ignition is turned on and ends when the ignition is turned off.

Charging events transmitted from en EV have a start time, end time, location, distance travelled (between charges), energy used (kWh), time charging and time-maintaining charge. A charge event starts when the vehicle's charging hatch (repurposed fuel hatch) is opened and ends when the charging hatch is closed. When an EV is stationary with ignition off and not charging, a parking event is created instead.

Charging stations require the user to identify himself/herself using an RFID tag before charging can commence. The station then logs customer IDs, start time, end time, as well as the amount of energy used for billing purposes. The charging station data is transmitted via GSM to an external server every four hours, from which a batch process downloads the data into the UWA server. The external server is checked every thirty minutes (see Fig. 15). Fig. 16 shows the energy drawn from a charging station from energy metre readings (solid) versus an estimated (ideal) charging profile (dotted).

The GPS tracking units can only log when they have a GPS fix, which usually requires unobstructed view of the sky for the GPS antenna [26]. Throughout the trial, vehicles were parked on occasions within heavy indoor areas, such as parking structures or underground, and have been charged without an active GPS fix. When vehicles have a gap in their data logging of greater than 15 min and have a battery level increase of more than 10%, a charge event is created for the duration of the data loss. In those cases, the charge event is created by estimation using the time the GPS signal was lost to the time the GPS was re-established as the start and end times. If a vehicle loses its GPS fix while driving, the distance between the point before GPS loss and the point of GPS re-establishment is taken to be the distance travelled during the period.

Over the length of the trial 73% (2256–3096) of the recorded EV recharging events occurred at 32 locations with a determined maximum power of 2.4 kW, 3.6 kW or 7.7 kW (10, 15 and 32 A sockets/stations at 240 V). When charging at 10 or 15 A sockets, the vehicles will draw 1.8 kW, while at 32 A sockets (charging stations), vehicles will draw only 4.8 kW, due to limitations in the in-vehicle chargers. The vehicles' charge currents were deliberately reduced on an 10 A outlet for safety reasons, as audits showed 20% of Australian households having serious electrical safety faults [27] and out of fear of damage to ordinary household power outlets when used for EV charging on a continuing basis.

Consequently, each location was categorised within GPS accuracy as either:

1. Home, at a EV users residence.
2. Business, at places of business such as work, but not at a charging station.
3. Stations, at one of the installed charging stations.
4. Other (unknown location).

3. Driving statistics

All EVs in the WA EV Trial are company fleet vehicles and some organisations have placed restrictions on their use, such as not allowing to take the vehicle home. This meant some of the EVs were only used throughout office hours. Also most vehicles were left idle on weekends. Some EVs had dedicated drivers, whilst others were shared pool vehicles with multiple drivers. Although the EVs used in the trial were similar to petrol vehicles, they were still a new technology and required some driver training on charge, range restrictions, etc. Most EV drivers were not reimbursed for electricity usage in their homes and did not have to pay for electricity used at work, which encouraged them to charge at work or at a charging system, rather than at home. These factors are described for each trial vehicle in Table 7.

Table 1 shows average distance, daily distance and distance between charges for each trial vehicle. In 2010 the average distance a passenger vehicle travelled for business in Western Australia was 11,700 km per year or 32.0 km per day [28]. The overall average for the trial over the length of the trial was 22.3 km per day, about two-thirds the West Australian average. The difference between the EV average and the West Australian average was caused by several factors:

- The vehicles were fleet cars, meaning that they would remain idle until they were needed and not be used as often as single user vehicles.
- Possible range anxiety meant that drivers would aim to take shorter trips, or when longer trips were required would take an ICE vehicle from the fleet.
- New users would require training generating smaller journeys that were not actual trips but simply an introduction to the vehicles.
- Some vehicles were used much more often than others because of poor perception of the technology in some companies or poor advertisement of its availability.
- Weekend days are counted but contribute very little of the total distance. Only 9% of the total distance travelled was on weekends but they account for 29% of the total time.

Table 1
EV journeys.

EV	Number of journeys	Average journey time (min)	Average journey distance (km)	Daily distance (km)	Distance between charges (km)
1	462	19.2	9.22	29.02	16.91
2	430	19.63	9.59	13.82	41.19
3	1121	13.56	7.77	21.71	21.12
4	339	22.16	13.46	11.9	21.46
5	1151	11	5.29	15.64	19.48
6	782	14.32	5.36	29.56	30.83
7	250	12.22	5.43	8.01	17.11
8	856	16.39	7.35	18.69	47.85
9	201	18.43	7.14	26.61	10.66
10	2180	21.31	12.23	50.86	40.23
11	1088	15.05	7.86	14.9	13.63
Avg.	805	16.65	8.6	22.3	24.86

Journeys accumulated over trial period years.

Over the trial period the EVs averaged 2.6 journeys per day. The annual energy usage is 1.55 MWh per EV for driving 22.3 km per. As for ancillary devices, we found that the air conditioner is turned on for 33% of the time, the lights 16% and the heater 3% of the time while driving.

Fig. 3 shows the distance travelled by time-of-day, with 91.31% of the total distance travelled occurring between 7 am and 7 pm. The peaks of distance travelled are at 7 am and 5 pm where vehicle 10 (which contributed 35% of the total kilometres driven)

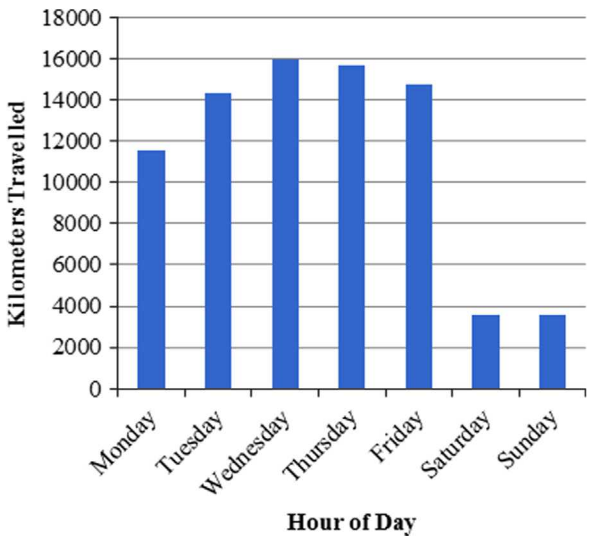


Fig. 4. EV travel distance by day of week for each of the 11 vehicles.

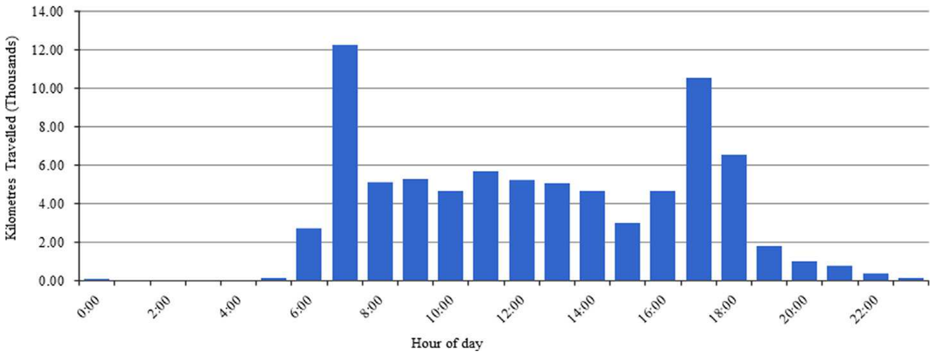


Fig. 3. EV travel distance by time of day for each of the 11 vehicles (1–11).

arrives at and leaves from work. About half (48.42%) of the total distance travelled is undertaken between the hours of 9 am–5 pm. The vehicles travelled 90.93% of their total distance on weekdays, with most vehicles not being used on weekends (see Fig. 4).

The kilometres travelled by time-of-day also outline the times when the vehicle needs to have a full charge. EV charging can be delayed or have its power level modified as long as the vehicle has a full battery by 6 am. Knowing this allows a smart charging station to better utilise renewable energy and/or take advantage of time-of-use energy tariffs (such as off-peak and on-peak pricing plans [29]).

4. Charging statistics

The number of charging events recorded over the duration of the trial is 2917, with 611 (20.95%) charges not charging to full. The charges are made up of 390 home charges, 963 station charges, 1189 business charges and 375 charges in unknown locations. In these locations 1339 charge events occurred at a high-powered outlet (Level-2: 32 A) and 1203 at low-power outlets (Level-1: 10 A or 15 A) with 375 at an unknown location and socket. Of the number of charges that were stopped before the vehicle was fully charged, 69 occurred at high-powered outlets (13% of all high-powered charges), 141 occurred at low-power outlets (24% of all low-powered charges) and 26 occurred at an unknown location (34% of all unknown charges) (Figs 5 and 6).

The charging statistics shown in Table 2 show the average charging time for EVs at a higher-powered socket is 1 h 25 min and at a lower-powered 10 A socket the vehicles are charged in 2 h 43 min. After the vehicles are charged they remain plugged into the socket for 16 h 20 min on average. Of the total time parked only 10.57% is spent for charging. In Table 3 we show, on average, the EVs were not being driven for 96.15% of the time, or 23 h 4 min per day.

Table 4 shows the parking percentages and charging probabilities in known locations (home, work, or station) versus unknown locations. If multiple staff members got to take the car home and charged it there, some of the 'home charging' events may have shifted to 'elsewhere charging'.

Table 5 shows the probability of charging when parked at a location registered as home, work, station or unknown. The probability of charging is based on the number of parking events at a location versus the total number of charging events. EVs driven and parked at the drivers' homes were recharged only 31% of the 1011 times parked. EVs at the various known business locations were recharged 60% of the 1765 times parked and those parking at charging stations charged 88% of the 1015 times parked. EVs were parked at 5058 different unknown locations and charged at those locations 7% of the times parked. On average 78% of an EV's total parking time occurred in 10 different known locations and on average 90% of recharging time occurred in seven different known locations.

Table 6 shows that for all the EVs in the trial, 89% of charges took place in each EV's top three locations, with on average 82% of charging taking place in the top two locations for each EV.

4.1. Charging power

The power (kilowatts) drawn by the trial EVs over time-of-day are shown in Fig. 7. The station and business charging power peaks as the EVs return to work, which were taken home the night

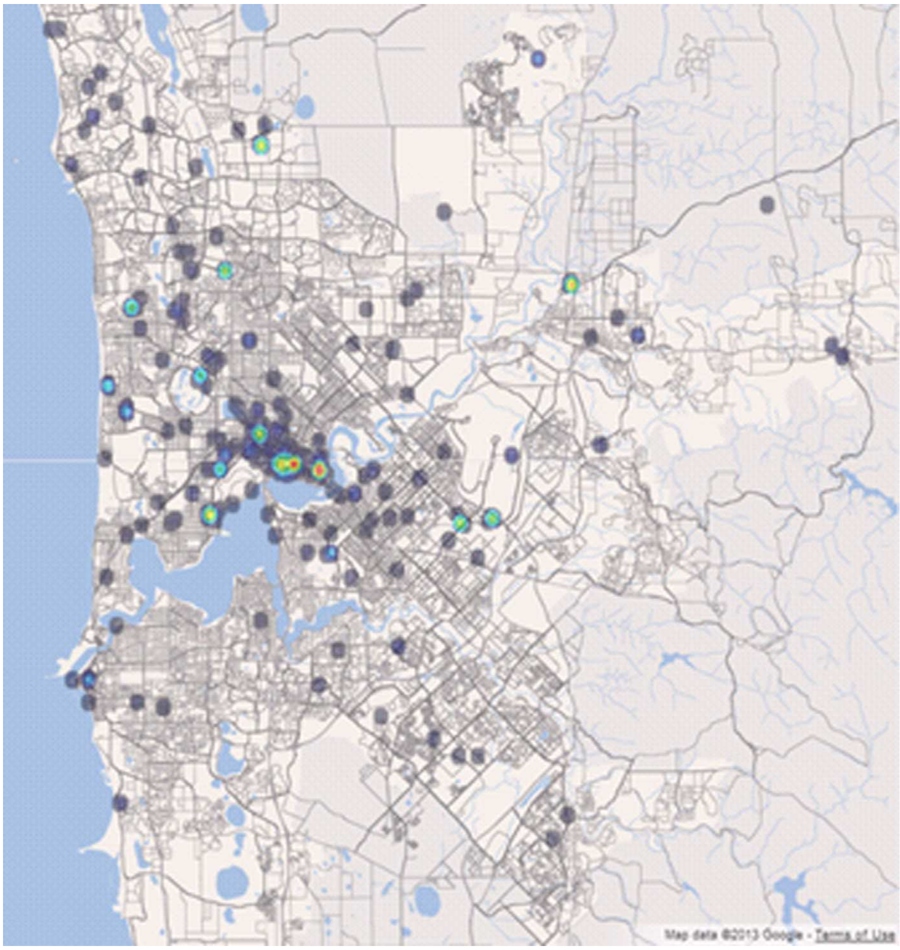


Fig. 5. Charging locations for the trial electric vehicles.

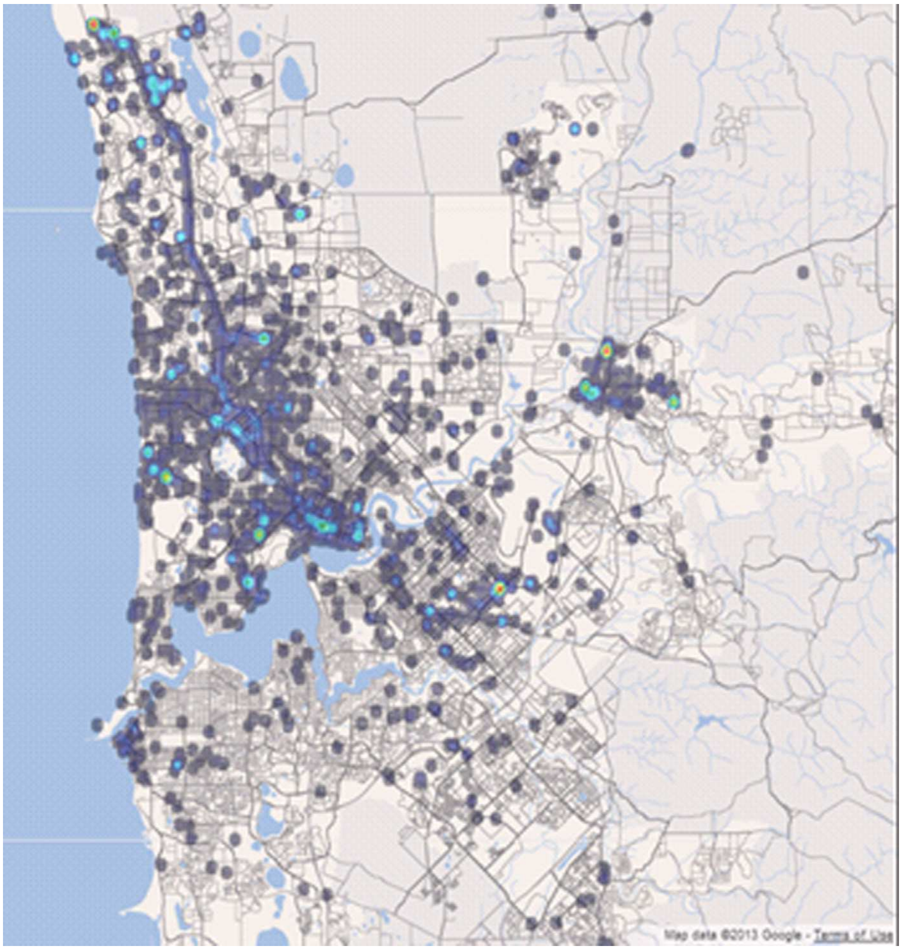


Fig. 6. Parking locations for the trial electric vehicles.

Table 2
Average energy and duration of charging.

EV	Avg. kWh	Average charging time	Average maintaining time	Charges at 10, 15 A	Charges at 32 A outlet	Charge time 10 A	Charge time 32 A
1	4.01	1:44:42	35:33:06	150	17	2:06:17	0:46:44
2	9.93	2:08:22	31:06:23	3	70	1:35:22	2:15:30
3	6.11	1:46:57	2:52:04	163	215	2:31:59	1:11:41
4	8.13	1:11:05	38:10:30	27	160	0:14:44	1:17:06
5	5.71	1:08:01	4:52:29	92	204	0:18:56	1:26:49
6	8.52	3:55:40	29:00:49	119	0	4:25:46	None
7	4.32	1:59:14	64:21:01	69	1	2:07:48	0:13:16
8	13.23	6:06:05	40:55:38	130	0	6:06:34	None
9	2.4	1:06:16	55:14:06	80	1	1:19:00	0:02:08
10	8.69	2:28:43	6:27:51	295	301	2:53:19	1:55:16
11	4.49	0:59:31	4:42:37	75	370	1:00:59	1:02:15
Avg.	6.62	1:55:52	16:20:13	109	122	2:43:09	1:24:45

Number of charge events, the amount of energy supplied and the charging time.

Table 3
Vehicle time usage.

EV	Logged time (h)	Driving time per day (min)	Time driving (%)
1	3524	1:00:25	4.25
2	7163	0:28:17	7.35
3	9631	0:37:52	4.32
4	9206	0:19:35	1.65
5	9336	0:32:32	2.00
6	3401	1:19:03	5.20
7	4067	0:18:02	4.08
8	8076	0:41:41	2.91
9	1294	1:08:41	4.33
10	12,584	1:28:37	6.43
11	13,768	0:28:33	2.04
Avg.	82,052	0:43:09	3.85

before. At 3 pm business power usage also spikes as the EVs are returned back to the businesses from their daytime trip. At 8 pm the home charging peaks as the vehicles that are driven home start slow charging. The power used slowly reduces throughout the night until the next morning.

Fig. 8 shows how often EVs travel a certain distance before being charged. In 83% of charge events the EV had travelled less than 60 km. With the maximum range of the vehicle exceeding 130 km, this shows that the usual behaviour of the EV is to travel less than half of the vehicle's maximum range before charging.

4.2. *Charging station statistics*

Fig. 9 shows the energy in kWh used by time-of-day for the duration of the trial. Of the total energy supplied, 26% occurred between 10 am and 12 pm, when the vehicles that were driven home arrive at a charging station to charge. 79% of the energy is

Table 4
Vehicle parking dynamics.

EV	Percentage parking time at known location (%)	Percentage parking time at unknown location (%)	Unique known locations parked	Unique known locations charged at
1	79.51	20.49	19	13
2	83.05	16.95	13	4
3	86.08	13.92	17	11
4	84.04	15.96	11	7
5	79.91	20.09	8	7
6	94.81	5.19	8	2
7	96.75	3.25	9	8
8	47.58	52.42	6	2
9	92.22	7.78	8	7
10	82.03	17.97	11	8
11	43.31	56.69	13	9
Avg.	77.90	22.10	11	7

Table 5
Charging location type.

EV	Charging probability ?at home (%)	Charging probability at work (%)	Charging probability at station (%)	Charging probability at unknown (%)
1	35.14	87.14	52.17	18.30
2	0.00	59.13	0.00	10.69
3	23.57	43.88	88.57	4.85
4	0.00	40.00	94.30	9.94
5	75.00	6.98	97.74	2.47
6	0.00	61.11	0.00	3.79
7	66.67	52.63	100.00	2.29
8	N/A	96.03	0.00	0.14
9	0.00	97.00	75.00	27.96
10	34.35	83.97	0.00	1.79
11	37.50	50.00	88.71	23.20
Avg.	30.86	60.11	87.59	6.80

Table 6
Common charging locations.

	1 (%)	2 (%)	3 (%)	4 (%)	5 (%)	6 (%)	7 (%)	8 (%)	9 (%)	10 (%)	11 (%)	Avg. (%)
Loc. 1	52	83	38	76	66	88	51	99	66	49	59	59
Loc. 2	23	13	15	10	18	12	27	1	24	34	29	23
Loc. 3	6	2	15	9	6	0	9	0	4	6	9	7
Total	80	99	68	95	90	100	87	100	93	89	97	89

Percentage of total charging energy (kWh) provided by top three used stations for each EV (accumulated over two years, each EV has different locations).

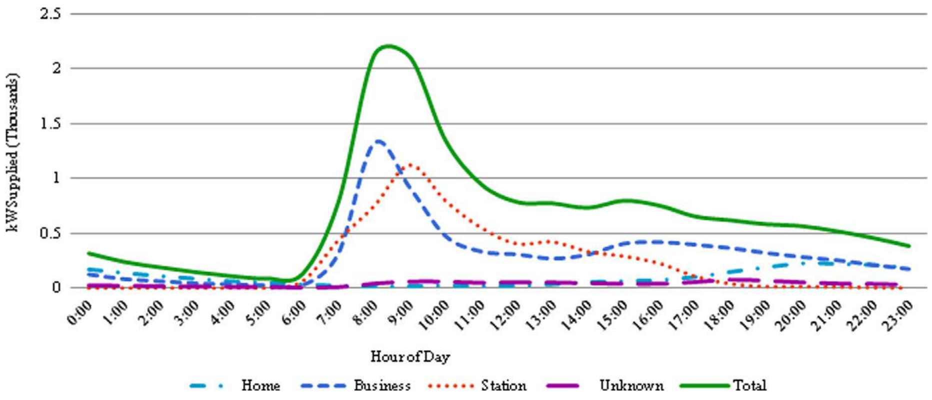


Fig. 7. Energy supplied at time of day.

used during daytime, between 8 am and 6 pm. This is during the times that solar PV panels generate power, which means charging stations are an ideal candidate for solar power offset.

When the vehicles are not charging they are maintaining charge, which consumes 24% of the total energy. It is important to note that maintaining energy usage is over the entire length of the trial and represents the energy needed to maintain the battery at full. This is effectively energy wasted, as it is not used to drive the vehicles, although it could be reduced substantially by configuring the vehicle chargers differently—e.g. to switch off until the battery charge level is degraded by more than 5%.

Fig. 10 denotes how the EVs are spending their time at a charging station. Charging stations were often occupied for a full work day, whilst only charging for a couple of hours. Only 8% of the time parked at a charging station was used to actually charge the EV whilst the other 92% was maintaining the vehicles' charge. The vehicles were completely charged during the maintaining time, only spending a small amount of their total parked time uncharged. This is over the length of the trial including the days when the vehicles were left idle at the charging stations, such as weekends and holidays.

During the length of the trial the charging stations that were most utilised were those located at or near an organisation that had an EV. The small number of EVs participating in the trial (including other private EV owners who had access to the stations) meant that the other stations were rarely used. The combination of this fact and the common charging locations (see Table 6) allows us to conclude that Level-2 charging stations are not necessary where EVs are not commonly parking. Charging usually happens in only one or two locations for each vehicle. These findings reflect on the necessity for high powered DC-charging stations, which were not available for this trial.

4.3. Energy tariffs

Fig. 11 shows the amount of energy used and the cost associated with a tariff and the flat-pricing plan, which were available at the time of the trial from the Western Australian electricity retailer Synergy. The tariff used a peak, off-peak, and shoulder segment, where the price for electricity changed depending on the time of day and season. The cost of electricity during an off-peak period is 11.32 cents/kWh, peak is 42.15 cents/kWh and shoulder is 21.44 cents/kWh. The winter months in Australia are April–September, while summer months are October–March.

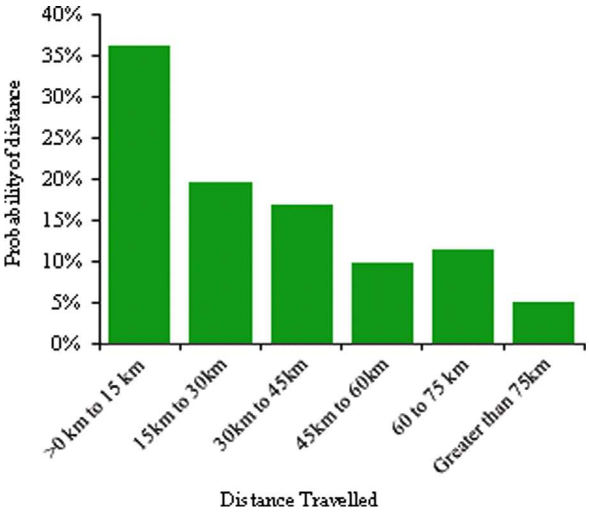


Fig. 8. The probability of travelling a certain distance before charging.

Fig. 12 shows the total energy used at charging stations over the length of the trial divided up into the different tariff plan pricings. The diagram shows a very large proportion (47%) of charging station EV charging took place within peak times and a very small proportion (6%) during off-peak times. The total cost when charging vehicles at charging stations using a tariff plan would have been AUD2221, which is significantly more when compared to flat-tariff pricing of 21.87 cents/kWh costing AUD1626. As the trial did not use incentives for the EV users to charge at certain times and no method of smart charging was available to the trial participants, the results do not reflect user-controlled pricing (where the EV driver knows and pays for the electricity), but rather a station owner perspective. The trial showed that without smart charging or user incentives, the available time-of-use tariff plan would have been be more expensive than the available flat-rate tariff for EV charging stations.

5. Related studies

5.1. Victorian EV trial

The Victorian EV trial with 42 EVs is currently underway in Melbourne, Australia using 14 Mitsubishi iMiEV, 16 Nissan Leaf, seven converted Holden Commodore, and five Blade Electron fully electric vehicles. It has released an interim report that contains some limited statistics [30]. Because there were various issues with data collection and transmission from the vehicles, the interim trial report only includes statistics on the daily distance driven and distance between charge events for the Leaf and the iMiEV EVs. The iMiEV travelled an average distance of 24.5 km per day and the Leaf travelled 32.8 km per day, which is more than the average of the WA EV Trial at 22.3 km. The distance between charge events was 34.3 km and 35.9 km for the iMiEV and Leaf, respectively, which is much longer than the 24.9 km that the Ford Focus averaged in the WA EC Trial. The difference in these values may be attributed to two major differences between the WA and Victorian EV trials:

1. The Victorian trial combines both fleet and household vehicles usage, while the WA trial was solely based on fleet vehicles (with some vehicles allowed to be taken home).
2. Driver confidence may be higher in the OEM-manufactured (original equipment manufacturer) cars of the Victorian trial than the after-market converted Ford Focus in the WA trial.

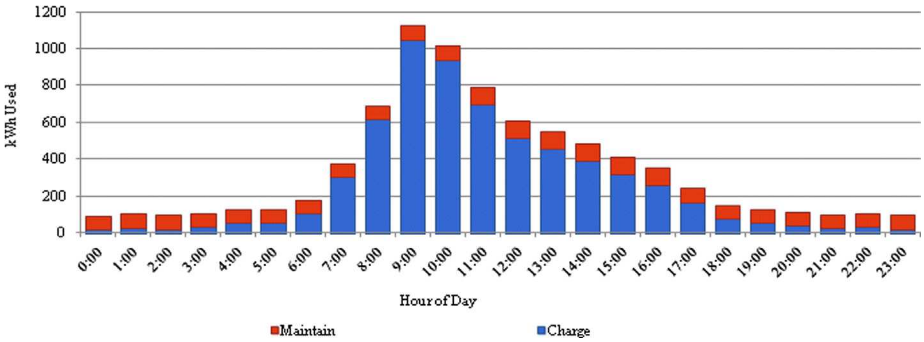


Fig. 9. Energy used charging and maintaining over hour of day for the length of the trial.

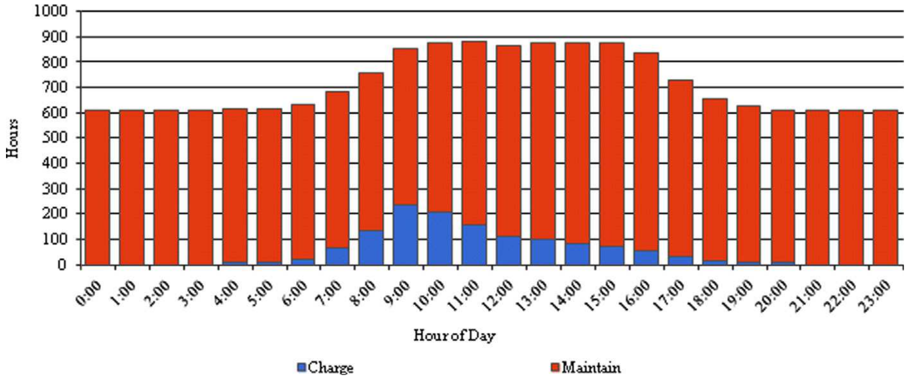


Fig. 10. Hours spent charging and maintaining charge over hour of day for the length of the trial.

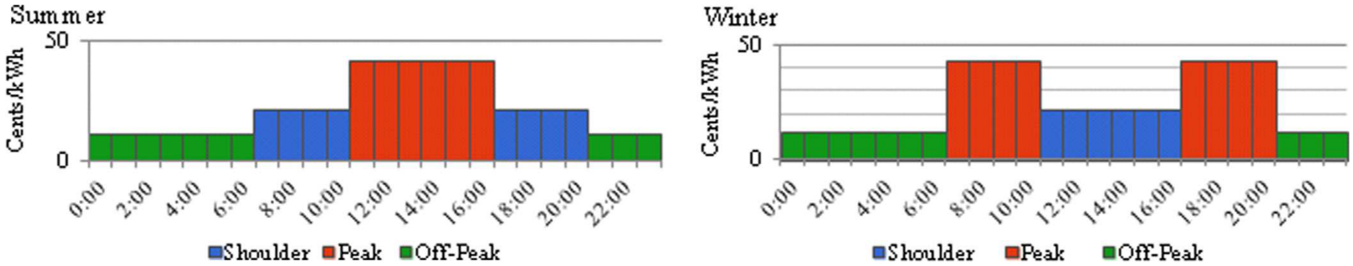


Fig. 11. Peak, Off-peak, Shoulder pricing tariff.

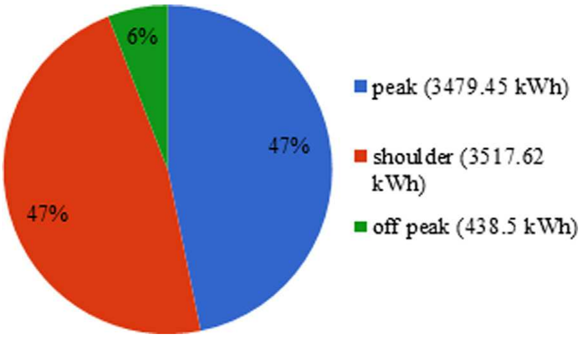


Fig. 12. Peak, shoulder, off-peak energy usage over the length of the trial.

5.2. Switch EV trial

The Switch EV Trial was conducted in North-East England from 2010–2012. It involved 45 EVs, 20 Nissan Leaf, 15 Peugeot iOns, eleven Avid CUE-Vs, two Liberty E-Range Range Rovers and one Smith Electric Vehicles Edison Minibus. The Switch EV Trial leased the vehicles to a mixture of organisations, councils, car clubs and individuals while tracking their usage. The trial participants were a mix of private drivers, individuals at an organisation and fleet vehicles. Some statistics from this trial is published in Ref. [31].

Similar to the analysis from the WA EV Trial, the Switch EV Trial charging statistics was separated into home, work, public and other locations. There was a peak between 9 am and 10 am when charging at a workplace, while the power curve in the WA EV Trial peaked between 8 am and 9 am (see Fig. 7). However the station charge curve from the WA EV Trial differs significantly from the public charging curve of the Switch EV Trial. This could be due to the following factors:

1. Location of the charging infrastructure.
   The WA EV Trial station charging relied heavily on the charging stations installed through the ARC Linkage grant, as there were very few other charging stations available. The stations that were utilised the most were located at the workplace of an EV Trial participant who had an Electric Ford Focus (and the power curve is similar to charging at work). The Switch EV Trial has its charging infrastructure distributed in different locations including shopping centres and car parks. For the Switch EV Trial this meant that a greater number of charges occurred during the day as the vehicles were parked at these locations.
2. Numbers of charging locations.
   The Switch EV Trial has a significantly larger number of public charging locations (268 versus eleven in the WA EV Trial). The larger number of Switch EV Trial public charging stations was a result of using existing infrastructure installed by EV charging station companies. As there were no commercial charging stations in WA before the trial, the WA EV Trial had access to fewer charging stations.
3. Charging station power output.
   The Switch EV Trial had a mix of Level 1 and Level 2 charging stations. Level 1 stations output less power and thus the EV will be charging for longer (about three times longer than Level 2). Level 2 stations charge the EVs faster and generate more of a peak. Because of this, a mix of Level 1 and Level 2 stations will generate a flattened, longer power curve. The WA EV Trial only utilised Level 2 stations and charged the EVs quicker. This results in higher charging power and shorter charging times, which results in a higher peak.

The home charging curves for both the WA trial and the Switch trial are very similar with a peak in the evening (between 19:00 and 20:00), although the quantity of home charges in the WA trial is significantly less because of the different configuration of the trials.

- The Switch EV Trial results show the recharging by location as:
- Individual users of fleet vehicles: 45% work, 31% public, 17% home and 7% other.
- Fleet pool vehicles: 38% work, 37% public, 18% home and 7% other.

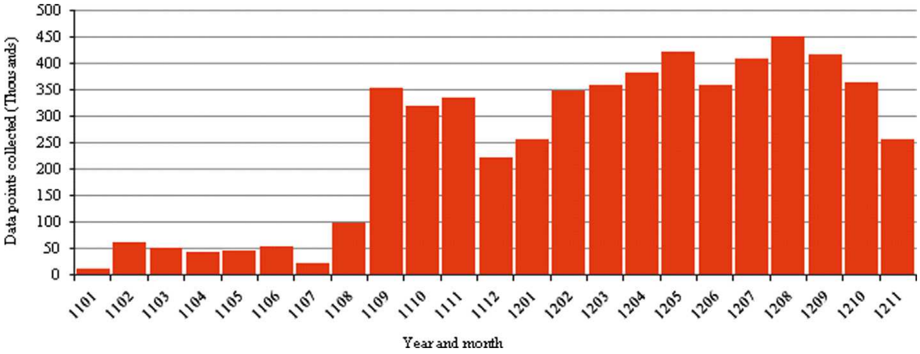


Fig. 13. Data collected over time.

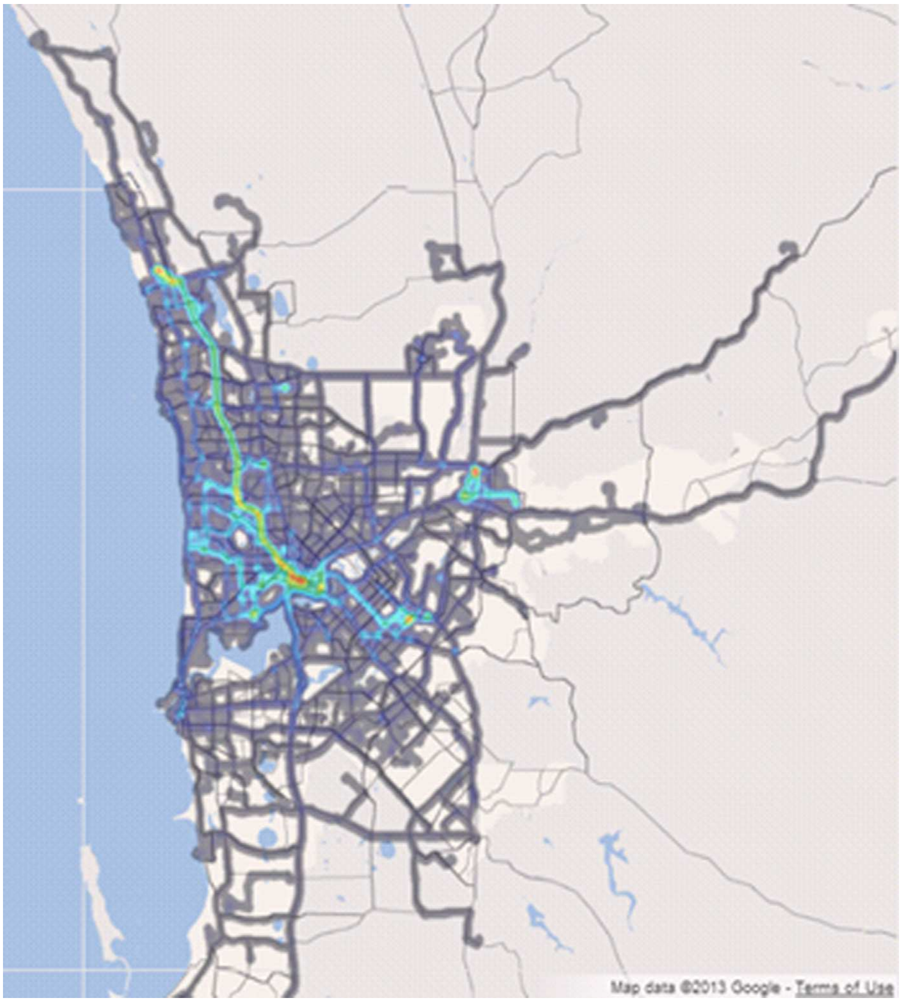


Fig. 14. Heat map of the vehicle movement throughout the trial.

- This is quite similar to the results from the WA EV Trial with the EVs charging patterns as:
- 41% work, 33% public (station), 13% home and 13% other (unknown).

The work and public results from the WA EV Trial sit between the individual users and fleet pool results from the Switch EV Trial. This is because the WA EV Trial has individual users and fleet users combined into one group (see Table 7). The bigger difference between the home and other charging results of the two trials is a result of the increased number of "other" locations for the WA EV Trial. A charge occurring at an unknown ('other') location may in fact have been a home location that had not been defined (e.g., multiple home destinations for cars used by multiple drivers).

5.3. CSIRO driving statistics

The CSIRO in collaboration with the University of Technology Sydney released a report in 2011 which assesses electric vehicles and their impact on the electricity grid [32]. Using data they obtained from the Department of Transport Victoria, 'Victorian Integrated Survey of Travel and Activity 2007' [33] they generated

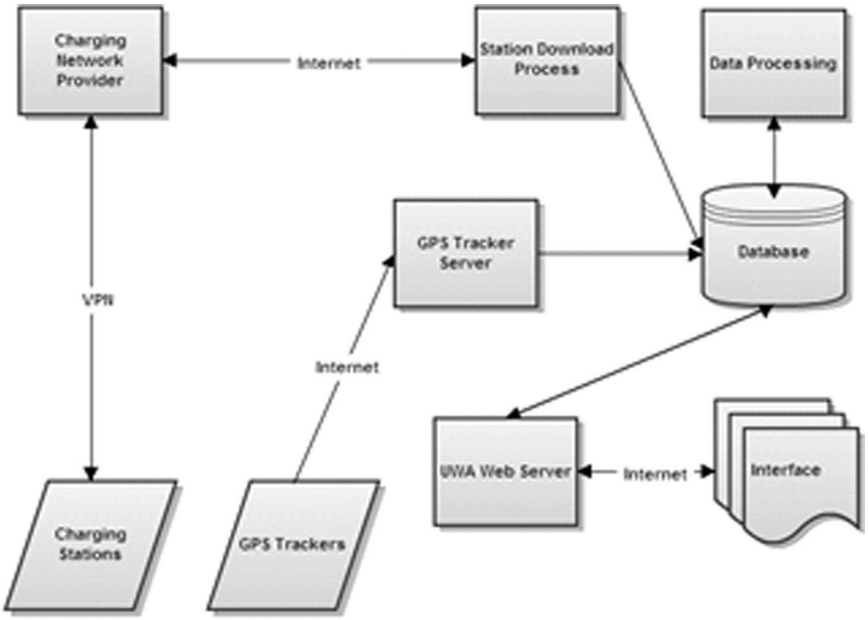


Fig. 15.

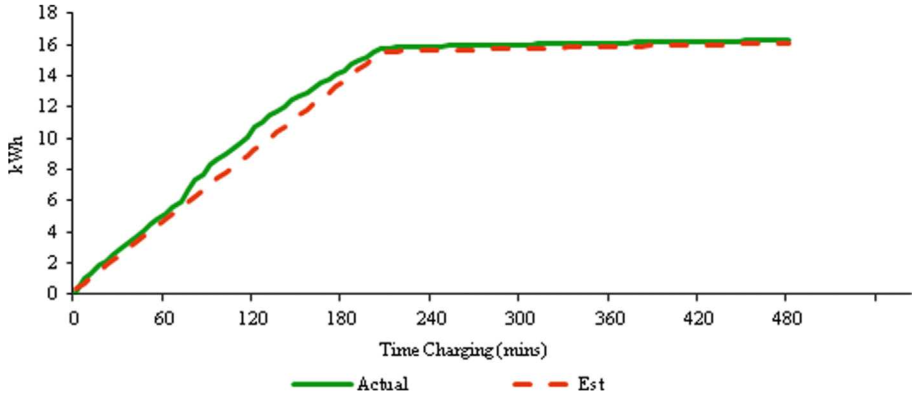


Fig. 16.

Table 7
Vehicle details.

Vehicle number	Single or multiple user	Vehicle take home	Weekend use	Percentage of journeys on weekend (%)	Percentage of distance on weekend (%)
1	Multiple	Yes	Yes	3.97	3.40
2	Multiple	Yes	No	0.00	1.54
3	Single	Yes	Yes	14.38	14.56
4	Multiple	No	Yes	3.83	1.60
5	Multiple	No	Yes	3.83	3.76
6	Multiple	No	Yes	4.67	5.65
7	Multiple	No	No	0.00	0.00
8	Multiple	No	No	0.36	1.62
9	Multiple	No	No	0.00	0.00
10	Single	Yes	Yes	27.67	16.84
11	Multiple	Yes	Yes	5.04	3.66

Vehicle description table, showing the variations between the different EVs.

a measured kilometres per hour during the week for ICE vehicles in Victoria, Australia. CSIRO used this information to simulate the average energy demand curve for EVs. The results of the Travel Survey for the weekday driving distance per hour are comparable to that of the WA EV Trial (see Fig. 3). The similarity between the two shows that the EVs are being used in a similar manner to ICE vehicles.

However, the CSIRO report's energy demand curve is simulated from the driving distance per hour and therefore does not compare to the power demand curves generated by the WA EV Trial or the Switch EV trial. The CSIRO simulation of power use for charging assumes that the vehicles will distribute their power usage throughout the entire time they are plugged in. This is not the case, as the vehicles can usually charge to full from a daily drive in a few hours on slow charge and about only a third of that time at a Level 2 charging station.

5.4. Comparison to simulation studies

Shahidinejad and Filizadeh [34] estimate the probability of charging for a Nissan Leaf and a Chevy (Holden) Volt using computer simulation based on vehicle telemetry data, and conclude a much lower probability of charging than what we found experimentally shown in Table 5. Two possible reasons why the EV drivers charged quite often are the driver's fear of running out of battery or because drivers want the maximum travelable distance available at all times.

The business and station charging patterns are similar to the workplace charge load simulated by Weiller [13]. Possible grid effects (or the lack of it) have been researched in Refs. [23,18].

Axsen and Kurani [35] used a web-based survey as a data set to simulate vehicle charging times, dividing their charging potential into home and workplace. In their simulation when workplace electricity is available they show a similar workplace electricity usage with a peak at between 8 am and 9 am. However, their simulation scenario has the majority of electricity used at home, peaking at 7 pm, whereas our EVs only generated a small energy peak at 4 pm. Kelly and MacDonald [14] developed scenarios from travel surveys to examine the charging times and energy used. They conclude that the peak for most charging will occur at 8 pm, again assuming that the majority of charging occurs at home. Ashtari, Bibeau [16] determine hypothetically that the majority of charging occurs between 6 pm and 7 pm, with a smaller peak in the morning at 7 am, by examining the movements of petrol vehicles. The difference between these studies and our results is likely caused by the influence of free charging at work and the availability of the vehicles outside of work hours.

6. Recommendations

The following recommendations are based on the WA Electric Vehicle Trial outcomes. The final report of the trial has been published as Ref. [33].

6.1. *EV uptake*

EV uptake has been quite slow in Australia compared to other countries.

- Some form of short-term government financial support or tax credit would help to kick start the uptake of EVs in Australia.
- With the recent introduction of OEM EVs into the Australian market, an opportunity exists for government organisations to lead by example by including EVs in their fleets. The fleet market will then feed the used car market with EVs in two years' time.

6.2. *Recharging infrastructure*

Level-2 charging stations are misused as free parking bays and occupied for exceedingly long times. It is next to impossible to provide an adequate number of Level-2 charging stations without either EV owners complaining about insufficient charging bays or petrol/diesel car owners complaining about vacant charging/parking bays.

- Small city-wide networks of fast-DC (50 kW) charging stations should be established where the driver will stay with the EV during charging, then move the vehicle.
- There should be no further efforts to extend medium-fast charging (Level-2) or slow-charging (Level-1) networks.
- Demonstration projects such as the proposed ‘Electric Highway’ (Perth to Margaret River) with a chain of charging stations should be funded to link the city to a popular holiday destination and enable EVs to leave the city. This would also have a positive effect on EV uptake.

6.3. *Standards*

Standards Australia has recommended adoption of IEC 62196, but has not recommended either charging connector (Type-1 for single-phase or Type-2 for three-phase).

- A lack of national charging standards is another factor limiting the uptake of EVs.
- Since Australia has a three-phase power grid (like Europe and unlike the U.S./Japan), the obvious choice would be to adopt IEC 62196 Type-2. All OEM EVs support this standard.
- Agreement on national EV standards in Australia will remove a major barrier to the establishment of recharging networks in this country. Failure to prescribe a particular connector/inlet type will lead to the import of cars and charging stations that are incompatible with one another.

6.4. *Electricity network implications*

The introduction of large numbers of EVs and EV charging stations may have significant implications for the management of WA's electricity network, which can be positive (e.g. increased energy revenue) or negative (e.g. higher peak load) for network operators.

- Time-of-use electricity tariffs may be able to ameliorate costs involved with meeting peak network demands and may potentially result in net system benefits.
- More research is needed in intelligent (smart) network protocols, which enable better management of vehicle recharging, and to better understand the potential electricity system impacts of EVs in general.
- Energy utilities, government policy makers and EV industry participants should work collaboratively to maximise the benefits from the introduction of this new transport technology.

7. Conclusion

EVs are now starting to appear on our roads, with several major automobile manufacturers producing them. A greater understanding of EV-driver behaviours is important to determine the impact EVs will have. Such an understanding will aid in determining how to power the EVs from renewable resources such as solar and wind power, minimising the GHG emissions. Our findings give evidence showing the effectiveness of installed charging infrastructure with EVs. With that evidence we are able to recommend in what, how and where organisations should invest in to maximise utilisation and minimise cost.

Our results showed that energy used by the vehicles to charge from the grid peaked between 8 am and 10 am as vehicles came into work. Charging stations supplied the most energy to EVs during the day, which could be offset by solar PV systems. Installed charging infrastructure is only consistently utilised when there is an EV daily commuting to and from the station and does not seem economically viable while there is such a low population of EVs. The average distance before charging was well below the maximum range of the vehicles with 83% of charge events occurring when the vehicle still has more than half of its maximum allowable range remaining. Large amount of time spent at charging stations was in maintaining charge (92% of the total time plugged in) not actually charging. This means that the charging stations are not being fully utilised while a vehicle is plugged in.

In the trial Level-2 charging infrastructure was used and was not fully utilised. From the driving patterns of the EVs we can see that the vehicles are usually parked and left charging in only one or two locations (at home or work). The EVs are generally left charging for a long time at these locations and do not require a full charge as they usually have a significant amount of energy left in their batteries. The additional cost for the Level-2 (7.2 kW) stations over the Level-1(2.4 kW) stations is not justified with such long maintaining charge times (parking without full-power charging) as the Level-1 stations will quite often fully recharge the EV.

From the study's findings we can also make some more involved conclusions. The purchase of level 1 or level 2 charging stations for public usage will not be properly utilised whilst there is still such a low number of EVs who have many other opportunities to recharge. Also in these public networks, the energy supplied from the station is not as utilised as the parking space is, making it difficult to profit off electricity consumption alone. These public networks will be likely installed and maintained to encourage EV usage, without being profitable on their own.

There is room in the market for the installation of a smaller fast-DC charging network in favour of a larger Level-2 AC network which would satisfy EV driver's rare need for a quick full recharge. At fast charging stations EV owners would then have to stay with their cars during the charging process, which would become very similar to the refuelling of a petrol or diesel vehicle.

Level 1 charging stations should still be purchased privately. Organisations which want to reduce their GHG emissions and running costs through the purchase of EVs should invest in charging infrastructure for their vehicle and also install solar PV. The station will be well utilised as it is the primary charging location for an EV (we showed that an average of 60% of charging will occur there). Also, the station also supplies safety, security and logging that allows an organisation to keep track of energy usage. The risks involved in charging an EV make it very important that organisations have the industrial EV charging standard connectors and cables and other electrical safety devices which are built into charging stations. Finally, only a Level 1 charging station is necessary in this circumstance because of the long parking times allowing for slower charging, and reducing the cost of the station. A solar PV system will also be properly utilised, as the power typically supplied to the electric vehicles is throughout the daylight hours.

Acknowledgements

The authors would like to thank the organisations that participated in the WA EV Trial and the ARC Linkage Charging Project including—CO2Smart, EV Works, the West Australian Department of Transport, Mainroads WA, the Water Corporation, the Department of Environmental Conservation, Landcorp, City of Swan, City of Perth Parking, The West Australian, Telstra, RAC, City of Mandurah, City of Fremantle, Galaxy Lithium, EMC Solar, Murdoch University, UWA Business School, UWA Engineering, and the Australian Research Council (funded through project grant no. LP100100436).

References

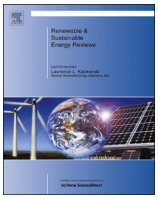
[1] Green Ii RC, Wang L, Alam M. The impact of plug-in hybrid electric vehicles on distribution networks: a review and outlook. Renew Sustain Energy Rev 2011;15(1):544–53.
[2] Fakhra Jabeen SS, Doina Olaru, David Harries, Thomas Bräunl. Acceptability of electric vehicles: findings from a driver survey. Australian Transport Research Forum; 2012.
[3] Western Power Annual Report; 2011.
[4] Schultz A, Petchey R. Energy update; 2011.
[5] Faria R, Marques P, Moura P, Freire F, Delgado J, de Almeida AT. Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles. Renew Sustain Energy Rev 2013;24(0):271–87.
[6] Erol-Kantarci, M Mouftah HT. Prediction-based charging of PHEVs from the smart grid with dynamic pricing. In: Proceedings of IEEE 35th Conference on Local Computer Networks (LCN); 2010.
[7] Mets K, De Turck F, Develder C. Distributed smart charging of electric vehicles for balancing wind energy. In: Proceedings of the IEEE Third International Conference on Smart Grid Communications (SmartGridComm); 2012.
[8] Mischinger S, Hennings W, Strunz K. Integration of surplus wind energy by controlled charging of electric vehicles. In: Proceedings of the 3rd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies (ISGT Europe); 2012.
[9] Tulpule PJ, Marano V, Yurkovich S, Rizzoni G. Economic and environmental impacts of a PV powered workplace parking garage charging station. Appl Energy 2013;108(0):323–32.
[10] San Román TG, Momber I, Abbad MR, Sánchez Miralles Á. Regulatory framework and business models for charging plug-in electric vehicles: infrastructure, agents, and commercial relationships. Energy Policy 2011;39 (10):6360–75.
[11] Dallinger D, Wietschel M. Grid integration of intermittent renewable energy sources using price-responsive plug-in electric vehicles. Renew Sustain Energy Rev 2012;16(5):3370–82.
[12] Brown S, Pyke D, Steenhof P. Electric vehicles: the role and importance of standards in an emerging market. Energy Policy 2010;38(7):3797–806.
[13] Weiller C. Plug-in hybrid electric vehicle impacts on hourly electricity demand in the United States. Energy Policy 2011;39(6):3766–78.
[14] Kelly JC, MacDonald JS, Keoleian GA. Time-dependent plug-in hybrid electric vehicle charging based on national driving patterns and demographics. Appl Energy 2012;94(0):395–405.
[15] EPRI, Transportation Electrification: A Technology Overview; 2011.
[16] Ashtari A, Bibeau E, Shahidinejad S, Molinski T. PEV Charging Profile Prediction and Analysis Based on Vehicle Usage Data. IEEE Trans Smart Grid 2012;3 (1):341–50.
[17] Srivastava AK, Annabathina B, Kamalasadan S. The challenges and policy options for integrating plug-in hybrid electric vehicle into the electric grid. Electr J 2010;23(3):83–91.
[18] Mullan J, et al. The technical, economic and commercial viability of the vehicle-to-grid concept. Energy Policy 2012;48:394–406.
[19] Richardson DB. Electric vehicles and the electric grid: A review of modeling approaches, Impacts, and renewable energy integration. Renew Sustain Energy Rev 2013;19(0):247–54.
[20] Göthel J, Bräunl T. editor. BMW, E1-33; 2012.
[21] AECOM. Economic Viability of Electric Vehicles; 2009.
[22] Järvinen J, Orton F, Nelson T. Electric vehicles in Australia's national electricity market: energy market and policy implications. Electr J 2012;25(2):63–87.
[23] Mullan J, Harries D, Bräunl T, Whitely S. Modelling the impacts of electric vehicle recharging on the Western Australian electricity supply system. Energy Policy 2011;39(7):4349–59.
[24] Gerardi W. Electricity Markets and the Uptake of Electric Vehicles; 2009.
[25] Commission IE. Plugs, socket-outlets, vehicle connectors and vehicle inlets – Conductive charging of electric vehicles – Part 1: general requirements. Int Electrotech Comm 2011:151.
[26] Kaplan E, Hegarty C. Understanding GPS Principles and Applications: Principles and Applications. Norwood: Artech House Books; 2005.
[27] MEA. Switch Thinking – Preventing Electrical Deaths in Australian Homes; 2011. 〈http://issuu.com/master_electricians/docs/switch_thinking_report?mode=window〉.
[28] ABS. Survey of Motor Vehicle Use, A.B.o. Statistics, editor; 2011.
[29] Kristoffersen TK, Capion K, Meibom P. Optimal charging of electric drive vehicles in a market environment. Appl Energy 2011;88(5):1940–8.
[30] Creating a Market, Victorian Electric Vehicle Trial Mid-Term Report, V.D.o. Transport, editor; 2013.
[31] Robinson AP, Blythe PT, Bell MC, Hübner DY, Hill DGA, Analysis of electric vehicle driver charging behaviour and use of charging infrastructure. In: Proceedings of the 8th World Congress on Intelligent Transport Systems. Vienna, Austria; 2012.
[32] CSIRO. CSIRO electric driveway project plugging. In: A Technical and Institutional Assessment of Electric Vehicles and the Grid in Australia Phase 1 Report; 2011.
[33] Victoria DoT. Victorian Integrated Survey of Travel and Activity 2007, D.o.T. Victoria, editor; 2009.
[34] Shahidinejad S, Filizadeh S, Bibeau E. Profile of charging load on the grid due to plug-in vehicles. IEEE Trans Smart Grid 2012;**3**(1):135–41.
[35] Axsen J, Kurani KS. Anticipating plug-in hybrid vehicle energy impacts in California: Constructing consumer-informed recharge profiles. Transp Res Part D: Transp Environ 2010;15(4):212–9.

Renewable and Sustainable Energy Reviews 60 (2016) 1213–1224

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



Leaving the grid—The effect of combining home energy storage with renewable energy generation[☆]

Stuart Speidel[a], Thomas Bräunl[b,1]

[a] The University of Western Australia, EECE/REV, Perth, Australia
[b] The University of Western Australia, School of Electrical, Electronic and Computer Engineering, 35 Stirling Highway, Crawley, Perth, WA 6009, Australia

ARTICLE INFO

Article history:
Received 8 May 2015
Received in revised form
29 October 2015
Accepted 23 December 2015
Available online 14 March 2016

Keywords:
Renewable energy
Local energy storage
Off-grid
Grid independence
Electric vehicles

ABSTRACT

Household renewable energy generation through the use of solar panels is becoming more commonplace as the installation cost is reducing and electricity prices are rising. Solar energy is an intermittent source, only generated during the day subject to interference from weather and seasonal variation. Energy storage solutions such as Lithium Ion batteries are also reducing is cost and have become a viable solution for storing the solar energy generated for use at other times.

In this paper we discuss the feasibility and limitations of various renewable energy, energy storage, feed into grid and off the grid systems. We also explore the results of our case study, The University of Western Australia's Future Farm, which featured a 10 kW solar system with 20 kWh battery storage, off the grid. Finally we use West Australians daily energy usage information to model the energy and savings of installing solar panels, home energy storage and using an electric vehicle.

Contents

[☆] This research has been supported by the Australian Research Council under Linkage Grant LP100100436.

E-mail addresses: sjmspeidel@gmail.com (S. Speidel), braunl@ee.uwa.edu.au (T. Bräunl).
[1] Tel.: +61 8 6488 3897, fax: +61 8 6488 1168.

http://dx.doi.org/10.1016/j.rser.2015.12.325
1364-0321/

1. Introduction

Being of the grid is a reality for many Australian farms. Not by choice, but simply because they are too far off the beaten track. Today, leaving the grid may become an interesting option for home owners even in suburban or city locations, when combining local energy generation with local energy storage.

Whenever the feed-in tariff is equal or higher than the cost for buying energy, the grid can be used as a very convenient energy buffer, i.e. generate enough energy during the sunshine hours for a full day's energy requirements, feed back to the grid all the surplus energy, and draw back from the grid during the dark evening and morning hours.

However, many countries still have now discontinued the generous feed-in tariffs of the past, so this method will not work anymore. Germany, for example has a feed-in tariff of 0.1315 EUR per kWh [1], while buying energy from the grid costs 0.27 EUR per kWh [2] as of July 1st 2014. In Western Australia (WA) the situation is even more extreme. The energy utility only pays 0.09 AUD per kWh [3] of home-generated green energy, while buying from the grid costs 0.26 AUD per kWh [4]. In addition, WA's energy retailer has reserved the right to approve feed-in from any energy generator above 5 kW, so larger solar PV systems may not be allowed onto the grid, and the utility also does not guarantee to buy any generated energy (even at the low price) at times of low demand and high renewable generation (i.e. around mid-day).

These circumstances plus the monthly grid-connection fees make local energy storage systems a very interesting option. They will reduce dependence on the grid by maximizing one's own generated renewable energy usage, up to allowing one to completely leave the grid.

The interest and demand for integrated home battery storage is currently booming. Some manufacturers are now introducing energy storage integrated into their solar inverters with the aim of reducing the amount of energy needed from the grid [5]. There is also a large amount of research going into solving the issues associated with such systems, such as generation and storage selection optimization [6]. The Australian government is also getting involved by funding a pilot project for small scale energy storage for households [7].

The University of Western Australia constructed the Future Farm as a best practice farm using the technologies we have available today to show the potential for farms in the future. The farm has been completely off the grid for over a year using solar panels and battery energy storage. During this time the farm saw its energy demand dramatically increase through the installation of an electric reverse-cycle air-conditioning and heating system, which brought the installed solar PV/battery storage combination to its limits.

The need to generate more energy than needed on a daily basis, in order to cover for extreme weather combinations (i.e. several cloudy days in a row), leads to inefficiencies where the potential energy generated by the panels cannot be utilized and only a fraction of the stored energy is required on an average day.

In this paper we look at domestic energy generation and storage, the effectiveness of these solutions, a tool for automatically estimating the associated data, and a case study of an off the grid solution.

2. Local energy generation

There are several commercial options available for local energy generation, including solar PV, thermal electric, wind/wave converters, biofuels, tidal schemes, hydroelectric energy and geothermal energy [8]. The ability of these systems to generate electricity depends on the location of the dwelling, its surrounding geography and weather conditions. In some applications even a combination of these methods generate the best solution [9]. Thermal electric, geothermal, wave, tidal and hydroelectric systems are only viable on a commercial scale or in very specialized locations. The two most commonly available and popular domestic power generation systems are solar PV and wind turbines. Biogas can also be converted to electricity domestically using a fuel cell, which is also discussed.

2.1. Solar PV

Solar photovoltaic systems (PV) use multiple photovoltaic modules to convert sunlight into DC electricity. The DC electricity produced can be used to charge DC batteries or supply a DC AC inverter to supply power to a household. Solar PV systems for household applications in Australia are generally sold in sizes ranging from a 1.5 kW to a 5 kW system, which is mostly due to government incentives in the past, rather than available and suitable roof space. On average in Western Australia per kW of nominal system size, a solar system will generate 1600 kWh of energy per annum [10].

The average solar system cost (including installation) by city and nominal system size was generated by Solar Choice in June 2013 [11]. This information was collected from 125 different solar installation companies around Australia and is shown in Table 1.

It has also been shown that solar resources can have their output behavior quite accurately estimated through measurements of solar radiation and ambient temperatures. In [12] they show that it is possible to predict the steady-state behavior of a grid connected network in a statistically reliable way. In this case grid connected, such predictions allow for more analytical approach do determining solar systems viability.

Table 1
Average cost of purchasing and installing a solar PV system in Western Australia and Australia (in AUS). The daily kWh is assuming that 1600 kWh is produced per annum per kW solar PV system. AUD are used.

System size	**1.5 kW**	**2 kW**	**3 kW**	**4 kW**	**5 kW**
Approximate Daily kWh in WA	7 kWh	9 kWh	13 kWh	18 kWh	22 kWh
Perth, WA	$3235	$4080	$5525	$7110	$8227
Australia	$3692	$4549	$6082	$7835	$9146

2.2. Wind

Wind power is generated by converting wind energy into electricity using a wind turbine. Wind energy is a very attractive option in Australia and is expected to provide the large share of the Australian 20% renewable energy target, set for 2020 [13]. Recently during wild weather conditions South Australia found that almost half of its total electricity demands were provided by their wind farms, and nationwide wind/powered more than 2.2 million households [14]. Wind turbines are available on both the domestic and commercial scale and Mithraratne [15] discusses through the use of a life cycle analysis that domestic wind turbines are significantly less powerful than larger commercial variants up to a factor of 11 in New Zealand. Mithraratne also goes on to say that domestic wind turbines are not powerful enough to supply the entirety of the household power without significant reductions in power usage through other methods such as insulation and efficient appliances/heating systems. They are however, an option to generate electricity locally and are available commercially.

Wind turbines available on the domestic scale generally operating at less than 10 kW with a one to five meter turbine radius with a cost ranging from $2000 to $10,000 [16]. Alam et al. [16] performed a small survey of available wind turbines in 2012 in Australia. Their results shown in Table 2 are combined with the power curves supplied by the manufactures.

The amount of power that can be generated from a wind turbine in an open air stream is proportional to the third power of wind speed. This means that when the wind speed doubles, the power output of a wind turbine can increase eightfold and so placement of a wind turbine is paramount to its effectiveness. This has been confirmed through field trials in [17]. The annual average wind speed in the Perth metropolitan area is 3.3 m/s in the morning and 4.4 m/s in the afternoon [18] The wind speed also varies at different times of the year going up to 5.3 m/s in the afternoon in summer and down to 3.6 m/s in the afternoon in winter. With these wind speed averages some locations could be viable for wind energy generation, however in domestic locations the variation in wind speed between different households is large.

There are several factors that affect the wind speed in areas with different local terrain and surface features. These include topographic speedup caused by hills and mountain ranges, thermal effects and funneling form weather systems, turbulence generation and gusts from terrain [19], cliffs, storm systems, shelter and obstacles such as trees buildings and other wind breaks [20]. In 2003 Coppin et al. [20] simulated wind speeds in a 80,000 km^2 section of NSW which showed the variation of wind speed. Their results show that the annual mean speed can vary wildly depending on topological conditions, where 0.02% of the land area produced more than triple the power of locations with mean wind speeds, and 15% of the land area generating 127% of the mean power.

Table 2
Cost of a sample of wind turbines in Australia.

Size	100 W	300 W	900 W	1000 W	1300 W
Power (5 m/s)	30 W	80 W	130 W	220 W	212 W
Cost (AUD)	$2000	$3500	$4100	$4300	$5500

2.3. Fuel cell, gas to electric

Fuel cells in different configurations can act as a generator or as an energy storage device. Here we are discussing fuel cells that are connected to a gas supply to generate heat and electricity. When connected to natural gas it is treated to remove the sulfur, then combined with steam to pre-reform other gases, leaving a methane rich gas. By connecting to the gas supply of a residential home, the commercially available product in Australia, BlueGen, can generate up to 1.5 kW peak output, with the added benefit of doubling as a water heater [21]. When generating 1.5 kW the system uses 9.5 MJ of gas per hour. The efficiency of such a system is 60% when used solely for electrical generation and 85% when used as a water heater. However this system still requires a fuel in the form of a gas such as natural gas, CNG, LNG, LPG or biofuels [13]. The BlueGen system currently retails at AUD 10,000 however this is three times the target mass market price. The cost of gas in Western Australia is AUD 0.12 per MJ, which means running the unit at full power from a natural gas supply would cost AUD 1.14 per hour or AUD 0.76 per kW. This is significantly higher than the cost of electricity from the grid at AUD 0.26.

2.4. Geothermal

Electricity can be generated from geothermal energy. This involves the drilling of wells into underground areas that are heated by the Earth's core. The three different types of geothermal power stations are: dry steam power plants, flash steam power plants and binary cycle power plants. Dry steam power plants use a direct geothermal steam of 150 °C or greater to turn a turbine. Flash steam power plants use high temperature and high pressure water of 180 °C into low pressure tanks which then turns into steam to drive turbines. Finally binary cycle power plants use moderately hot geothermal water as low as 57 °C which has its heat transferred to another fluid with a much lower boiling point than water, causing the secondary fluid to vaporize, driving turbines.

Geothermal plants are highly location dependent, and while geothermal energy can be used for local heating and cooling of homes it is not scalable to a single household when generating electricity. It is a source of renewable energy and does save money in the long term with no direct effect on the environment. However it does have a strong dependence of the individual household’s circumstances and high upfront costs.

3. Local energy storage

Some renewable energy generators such as Solar PV and Wind don’t generate their energy constantly, relying on sunlight hours and/or weather conditions such as wind speed and cloud cover. However the energy used by a household is required to be available on demand, consumed at any time of day [22] and must be reliably available to power devices such as fridges and freezers that contain perishables. Xiaonan et al. [23] discuss hybrid renewable energy systems in a single residential home, where they show the effects of varying energy availability and demand profiles, and how to optimize for system efficiency. This means that without some method of storing the energy generated by the temperamental renewable technologies the household would still need another energy source, such as an electricity grid connection. Also, even for grid connected households, local energy storage has the ability to maximize the usage of renewable energy generated due to the difference in electricity buying and selling prices [24].

To store electrical energy there are many options to choose from. The commercially available options tend to use Lithium Ion batteries because of their good energy densities. In this paper we will be focused on individual home energy storage systems however other solutions such as community energy storage are also feasible. As Parra et al. [25] discuss, in some situations shared community energy storage can have a significantly lower cost for electricity.

3.1. Storage system hardware

Energy storage systems require several components to operate, depending on the implementation. The energy storage system can be between the energy producer (wind or solar), and the load/grid or can be installed in parallel. The two different configurations are shown below.

In the first configuration (Fig. 1) the battery system is run in parallel with the energy producer. This has the advantage of easy installation, not needing the specifications of the solar system and being a cheaper unit. It has the disadvantage however of needing the electricity to be converted from solar DC to household AC and then to battery DC, converting the electricity twice, losing power to inefficiencies.

The second configuration (Fig. 2) is installed between the energy producer and the load/grid. This has the advantage of only converting the power once before storing it, reducing power loss. These systems are more expensive because of the different types and configurations of solar installations, requiring specific DC/DC converters. They also have a higher installation cost, and remove the old DC/AC converter from the solar installation (if existing) and requiring a new DC/DC and DC/AC converter.

The cost of an 8 kWh system available from BYD in July 2013 is AUS $19,000 for the parallel configuration and AUS $24,000 for the series configuration [26].

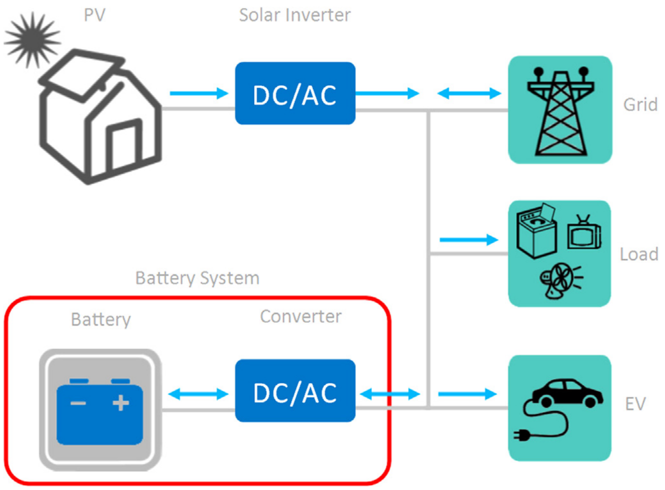


Fig. 1. Energy storage configuration not integrated with solar PV.

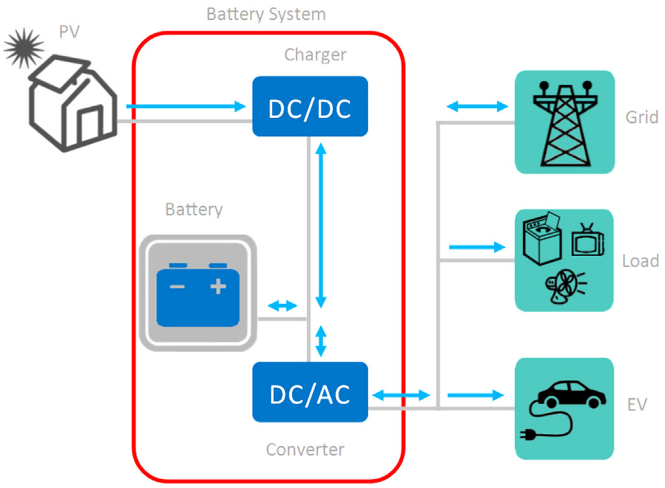


Fig. 2. Energy storage configuration integrated with PV.

3.2. Battery-based systems

Battery based energy storage is using a pack of batteries to store the renewable energy when excess is being produced and then to use the energy stored when needed. There are many factors that affect the cost, flexibility and storage capacity of a battery pack. There are differences between chemistries, between manufacturers and even between different batches of cells [27]. Here we will discuss some major battery chemistries with their varying energy density, maximum current, cost and lifetime of a battery pack. The different chemistries reviewed are listed below:

- Lead–acid batteries
- Nickel–cadmium
- Nickel–metal hydride batteries
- Lithium-ion batteries

Lead acid batteries can come in two types, 'deep cycle' and 'starting'. Deep cycle batteries are designed for applications that require a large amount of cycles with a low power output. Starting or SLI (starting, lighting, and ignition) lead acid batteries are designed to have fewer cycles with a greater power output. There are three different versions of lead acid batteries including Wet Cell (flooded), Gel Cell, and Absorbed Glass Mat (AGM). Wet cell batteries use an electrolyte fluid, which can be accessed for testing and replacement. In valve regulated lead acid batteries (VRLA), the fluid is inaccessible and they are considered to be sealed (SLA) and maintenance free. Gel Cells have a silica additive in their electrolyte that causes it to set up or stiffen. Gel cells are typically used in very deep cycle applications.

Lead Acid batteries have several disadvantages including a low energy density and long battery recharging duration [28]. Unsealed batteries require frequent maintenance of electrolyte levels and desulphation of the electrodes. A shorter battery life may result when applied to residential duty cycles and batteries have to be disposed as hazardous waste at the end of their life cycle [29,30]. The cycle life of lead acid batteries can range considerably based on its design. Typical configurations have 500 cycles with special configurations having up to 2000 cycles [27]. The low energy density of lead acid batteries makes them not very well suited to home energy storage.

Nickel Cadmium (NiCd) batteries are available in three different configurations; pocket-plate, sintered-plate and sealed. The plate and sintered plate are both vented batteries. The pocket-plate Nickel Cadmium batteries are heavy, with a low energy density, and have a higher cost than lead acid batteries. Their advantages are that they have a long life cycle, are reliable, retain their energy well are low maintenance and can withstand electrical and physical abuse. This makes the pocket-plate Nickel Cadmium batteries well suited for mission critical, emergency systems such as hospital power systems or trains emergency braking. The sintered plate was developed to increase the energy density of the Nickel Cadmium battery, having up to 50% more energy density than the pocket-plate configuration and improved performance [27]. The disadvantage of the sintered cells is the higher cost of the cells. These cells are usually used in applications where high peak power is required with a fast recharging time for example as a starter motor for aircraft or diesel engines. Sealed Nickel Cadmium batteries are not vented and do not require maintenance. Each of the configurations suffers from memory effect, which is a loss of capacity when cycled repeatedly on shallow discharges, this effect is reversible by completely discharging the battery. It is also important to note that Cadmium is environmentally damaging. Nickel Cadmium batteries have a long service life, usually greater than 500 cycles, and up to 1500 cycles with regular maintenance [31]. While they are suitable for home energy storage, their negative environmental impact and higher cost than equivalent lead acid batteries make them less suitable than other batteries.

Nickel–Metal Hydride (NiMH) batteries are an alternative to Nickel Cadmium battery chemistry. They have excellent safety, abuse resistance, cycle life, and energy density. Commercial NiMH typically have a cycle life of 600 – 1200 cycles to 80% capacity [27]. They are generally considered superior to the NiCd batteries because of their significantly better energy density and not being as harmful to the environment. However, after relatively few cycles their capacity drops significantly, whilst NiCd's capacity, internal resistance, and self-discharge remains relatively constant throughout its life [32]. In home energy storage systems, energy densities are not as important as cost and life time, NiMH batteries tend to be less suitable than Lithium Ion.

Lithium Ion batteries use the exchange of Lithium Ions between the positive and negative electrodes during their battery cycle. There are many different types of lithium battery chemistries, each having their own characteristics. Lithium Ion batteries have many advantages. They are sealed cells, requiring no maintenance, have a long cycle and shelf life, low self-discharge rate, and have high power and energy densities. The long life is typically greater than 1000 cycles, generally reducing capacity over time. A commercially available Lithium Iron Phosphate 'Thunder Sky' battery has 3000 cycles 80% initial capacity, and 4000 cycles 70% initial capacity [33].

Their disadvantages are that they have a moderate initial cost and require protective circuitry to prevent over power and energy charge and discharge [27]. The protective circuitry is usually provided by a battery management system, which protects the cells from damage. Lithium Ion batteries are very suitable for home energy storage, with a high capacity and long life time, there major disadvantage is cost.

3.3. *Flow batteries*

Flow batteries consist of two reservoirs of electrolyte fluid that flow through an electrochemical cell. The two most common electrolytes used are Zinc/Bromide and Vanadium Redox. Flow batteries have good specific energy, are energy efficient, use low cost materials are environmentally friendly, are adequately power dense, and can charge quickly [27]. The major drawback of this energy storage system is the overhead of pumps and control systems that increase the cost [34] and also increases the number of points of failure [35]. They also have poor energy density but can be suited to stationary applications such as home energy storage.

3.4. *Super capacitors*

Super capacitors are an alternative to battery storage in EVs, and have very high power densities. However they have very low energy density and significantly higher cost per kWh which makes them unsuitable for home energy storage systems.

3.5. *Fuel cells*

Fuel cells store electric energy by using electrolysis to produce hydrogen, which is then stored in a tank. When the electricity is needed, hydrogen and oxygen flow through an oxidation reduction to generate electricity [36]. A study by Caisheng Wang shows the feasibility of using fuel cell technology with PV and wind energy generation through simulation [37]. Though feasible theoretically, the cost of fuel cell systems is still very high and they are not yet commercial available in Australia for domestic energy storage applications.

3.6. *Pumped storage hydroelectricity*

Pumped storage hydroelectricity is a form of energy storage using the gravitational potential energy of water. Storing the energy is achieved by pumping water from a reservoir at a lower elevation to a reservoir at a higher elevation. Retrieving the energy can then be achieved by releasing the water back from the higher into the lower reservoir through a turbine, in which the flow of water generates electricity. For pumped storage electricity to be feasible, there must be an elevated reservoir with a very large capacity. Usually this configuration relies on the topography of a region, using areas with a large elevation difference. They are also not very scalable, requiring a large amount of infrastructure. Domestic pumped storage hydroelectricity would only be suitable in very limited locations. For these reasons it is not suitable for domestic home energy storage.

3.7. *Battery recycling*

Large cells of Lithium-based batteries are expected to be abundant worldwide within the next decade due to the market penetration of Electric Vehicles (EVs) [33]. When an EV has reached the end of its lifetime after around 10 years, the included Lithium Ion batteries still have a capacity of 80% from new [38] and can be used for stationary applications, such as home energy storage systems. The reduction in energy density does not affect a household greatly, so it makes sense to repurpose batteries from EVs ("second life batteries"), which will reduce the cost of domestic battery storage systems in the future.

Tong et al. [39] investigates the potential of second life lithium ion batteries as energy storage by recycling batteries from an electric vehicle. They found that the recycled lithium ion batteries were suitable for home energy storage and cheaper than new. This shows that the solution is viable were old lithium batteries exist.

3.8. *Energy storage capacity*

The sizing of energy storage is a widely covered topic.

4. UWA future farm

The University of Western Australia sponsored the creation of the Future Farm, a best practice farm for 2050 which provides the products of a conventional farm while minimizing the environmental impact. The UWA Future Farm was built in "Ridgefield" Pingelly in Western Australia around 158 km southeast of Perth. The farm was opened on the 20th of November 2009, containing 3924 acres, having an average rainfall of 425 mm and costing $5.3 million dollars. The goal of the farm was to provide research into several different enterprises including clean green and ethical animal production, 'No-Till' low water usage crop production, ecosystem maintenance and restoration, carbon farming and community collaboration.

The household is powered entirely by solar energy, with a 10 kW solar system (with two separate inverters) and a 10 kWh Lithium Ion battery storage system costing approximately AUD 90,000. The system has been logging data since July 2012, which has been extracted and analyzed for this report (402 days). The logging includes data points at half-hour intervals showing the total power consumption (energy from battery-storage and solar PV), power generated from the two solar inverters, battery level of the local battery storage system, and the level of solar irradiation.

The original design was based on an expected energy requirement of 17 kWh per day. However, the farm house had later two reverse-cycle air-conditioning units for heating and cooling installed, which together with poor insulation of the house increased the energy consumption to 36 kWh per day, more than double of the original design. The air conditioners require about 5 kW power when running in heater mode. No power failures had been recorded before installation of the air-conditioners were installed, but the farm house ran out of power six times over two winter months after their installation.

Possible solutions to avoid the intermittent power failures were as follows:

- Improve energy efficiency of house through better insulation and double glazing
- Increase size of battery storage system
- Use gas-heater instead of electric air-conditioning heater
- Use diesel generators as electricity backup
- Connect farm house to the electricity grid
- Use intelligent control systems to limit power consumption based of solar energy prediction systems

The system installed at the Future farm is relatively simple with no intelligent control. With solar forecasting systems [40] it is possible to predict days with low energy production, then limit the power consumption of lower priority systems. For example refrigerators and lighting would be considered high priority while heating may not. There are many examples of controlling renewable technologies with artificial intelligence [41], improving solar tracking and energy consumption.

In the end, a one-way grid connection was established that allowed drawing power from the grid on days of extreme weather conditions, but prohibited the export of generated solar energy to the grid, because the utility's aging rural grid was not able to cope with it. Switching between islanding mode and grid mode is done manually by farm staff.

Fig. 1 shows the average battery level and power usage (from solar PV and battery storage) over the trial period of more than one year. As the solar panels generate energy during the day, the batteries are charged. During the night the batteries are being discharged to power the household. Fig. 2 shows the complete battery depletion after three days of cloudy weather with only little solar energy being generated. Over this period several events occurred. On the 19th and 20th of June the solar panels could not provide enough energy to fully charge the batteries during the day because the energy demand of the household exceeded the limited charging energy in these weather conditions. This was not the main factor of the failure however, as shown on the 21st of June where the battery is significantly charged during the day (to 70% of its capacity), but the household still ran out of power at night because of the excessively high demand through running the air-conditioners in heating mode. The depletion of the battery then had a snowball effect. The solar PV could not fully charge it by the end of the next day and consequently, the batteries were depleted again on the following night (Fig. 4).

Not having a grid connection also prevents feeding in excessive solar energy on sunny days. Any excess energy from the solar PV when batteries are fully charged is wasted. Fig. 3 shows the potential energy that could have been generated is shown vs. the actual energy generated over the 402 day period. The area between the solar and expected solar line is the potential solar energy wasted. The expected solar energy is based off the average of solar generation being 1600 kWh per year for each kW of solar power in Western Australia. This comes to 16 MWh per year for the 10 kW system at the Future Farm. The total energy generated and used per day on average for the farm was 17.5 kWh, however the system should be capable of generating a daily average 43.8 kWh, so only 40% of the total potential of the solar PV system has been utilized. The system was over-dimensioned to ensure that the household would never run out of energy (with the original 17 kWh per day design consideration). This over-dimensioning is necessary for the operation of an off-grid location, such as a remote farm. A grid-connected system does reduce the necessity for over-dimensioning (energy can be bought from the grid for extreme situations) and also increases the environmental benefits through feeding-in excess solar energy Fig. 5).

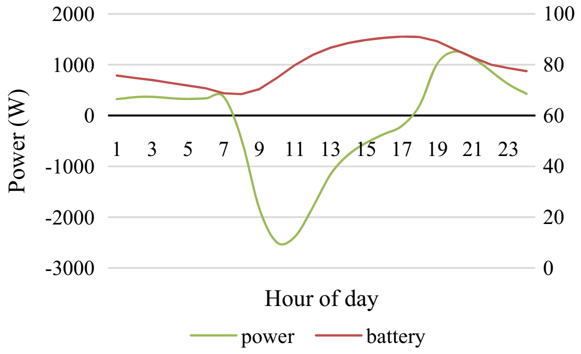


Fig. 4. Average power usage and battery level.

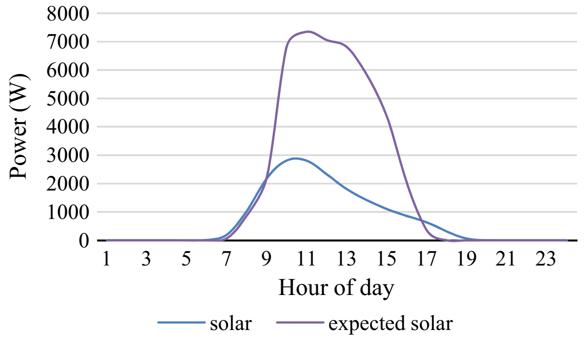


Fig. 5. Average used solar generation vs. average possible solar generation.

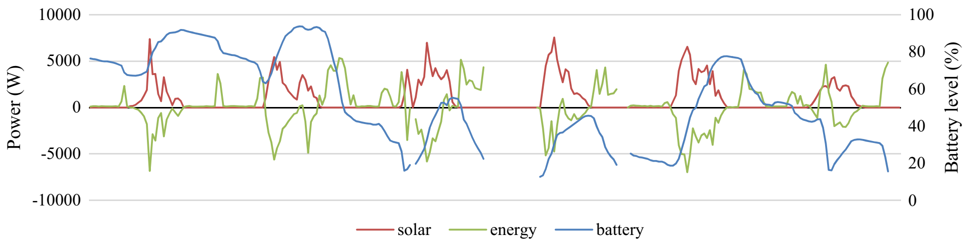


Fig. 3. Average power usage and battery level.

5. Models and sample data

We have designed a model to estimate power usage and savings in energy cost from a mixed PV, EV and battery storage system. The implemented web-based tool for this model displays results in graphical form as well as text and allows user input of several variables through slide-rulers. The information generated includes a graph of the kW used each hour over 24 h, and generates the following data for a full year:

- kWh bought from the grid and its associated cost to the household.
- kWh sold back to the grid and the associated revenue for the household.
- CO_2 saved from adopting solar panels, battery storage, and EVs for transport.
- Total percentage of renewable energy, which is the sum of solar energy and green grid energy bought vs. non-renewable grid energy bought.
- Annual equivalent petrol cost of driving the specified number of vehicles at the average daily distance.
- Annual energy amount (and cost) saved from installing solar PV and battery storage system.
- Total annual cost of buying electricity from the grid minus the revenue from feeding renewables into the grid.
- Annual cost for electricity (without provision and install)
- Annual savings, (comparing cost with and without the solar/storage/EV system).

There are seven variables available to the user, as shown in Fig 6. Each of them is discussed below in detail.

5.1. Number of EVs

The number of electric vehicles represents how many petrol internal combustion engine (ICE) vehicles have been replaced with electric vehicles in the household. The purpose of including EVs in the model is to show the user that EV technology has the opportunity to power transportation from renewable energies [42]. The number of EVs can be set from zero to four, which will affect the amount of energy required by the household, the petrol savings, the CO_2 saved, total annual cost, and saving. This also affects the average hourly energy distribution over the 24 h per day.

5.2. Solar PV

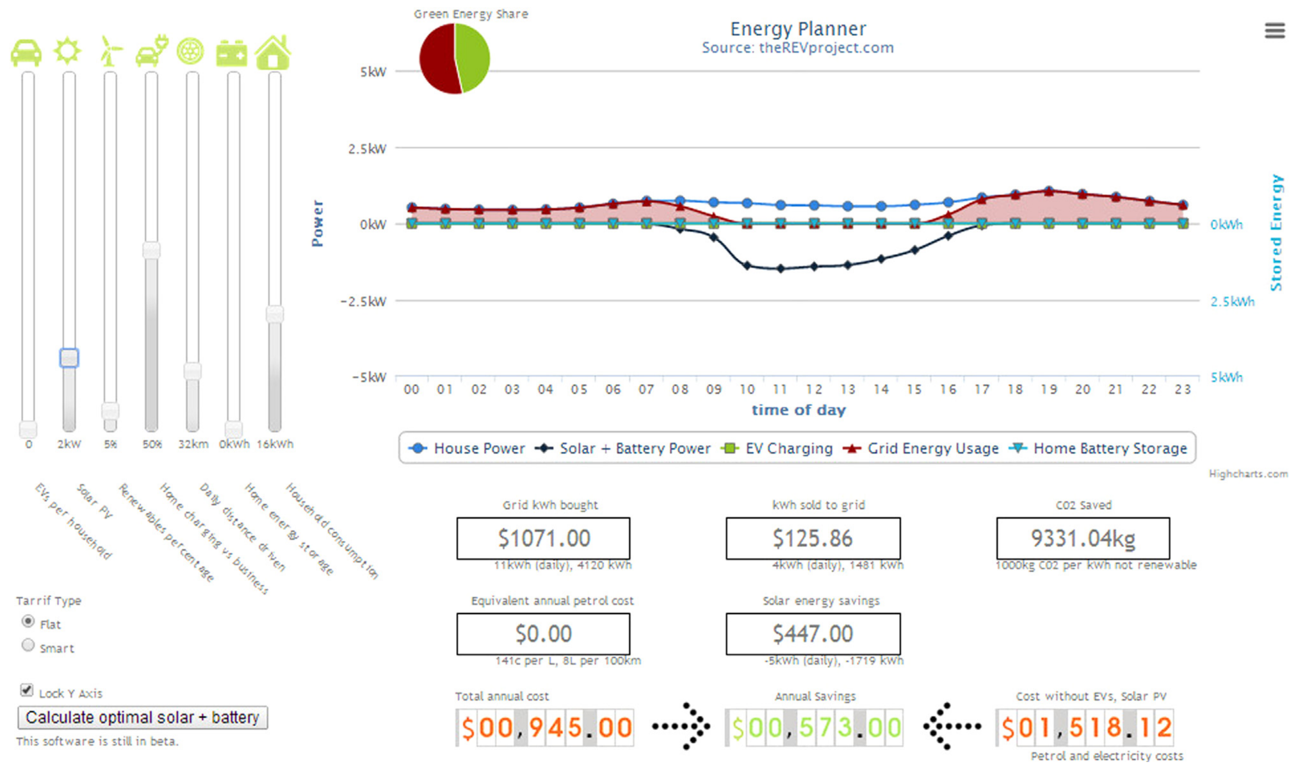
The solar PV system size can be set in kW. This affects the total energy generated, the amount of energy available to store, the CO_2 savings, the solar savings, the annual cost and annual savings. The solar energy is shown on the 24 h graph combined with the battery storage. With battery storage, solar energy can be stored when excess energy is produced, and used at later daytimes when needed. The model uses solar energy data from the UWA Ideal House project and assumes that per year per kW of PVs the solar panels will generate 1600 kWh of energy.

5.3. Renewables percentage

The renewables percentage is the percentage of electricity bought from the grid that is generated using renewable resources. This affects the CO_2 savings and the total percentage of renewable energy.

5.4. Home charging vs. business

This variable affects when the energy is being used for charging the electric vehicles. The 24 h energy usage for electric vehicles was taken from the WA Electric Vehicle Trial, in which eleven electric vehicles where monitored and tracked around Western Australia [43,44]. Using this information, the model can be adjusted for EV user behavior. The variable is the percentage of home charging versus work charging. During home charging, the



0 EVs per household
2kW Solar PV
5% Renewables percentage
50% Home charging vs business
32km Daily distance driven
0kWh Home energy storage
16kWh Household consumption

Tarrif Type
● Flat
○ Smart

☑ Lock Y Axis

Calculate optimal solar + battery

This software is still in beta.

Grid kWh bought: $1071.00
11kWh (daily), 4120 kWh

kWh sold to grid: $125.86
4kWh (daily), 1481 kWh

CO2 Saved: 9331.04kg
1000kg CO2 per kWh not renewable

Equivalent annual petrol cost: $0.00
141c per L, 8L per 100km

Solar energy savings: $447.00
-5kWh (daily), -1719 kWh

Total annual cost: $00,945.00

Annual Savings: $00,573.00

Cost without EVs, Solar PV: $01,518.12
Petrol and electricity costs

Fig 6. Household with 2 kW peak solar PV.

energy used by the EV to charge is in the evening when the vehicle returns home from work, peaking at around 8 pm. The EV will then charge overnight. During work charging, the EV charges when the EV arrives at work. Even though in this case the charging energy is consumed outside the household, the cost and CO_2 emissions are still associated with the household and therefore included in the model. The work charging peaks at around 9–10 am in the morning with a smaller peak in the afternoon for when the EV is used for additional trips during the day. The hour at which the EV charges is important as the energy produced by the solar PV system occurs only during daylight hours.

This variable affects all outputs from the model except the equivalent petrol cost and cost without the system.

5.5. Daily distance driven

The daily distance driven is the average km driven per day by a household vehicle (petrol/diesel or EV). In 2010 the average distance a passenger vehicle traveled in Western Australia was 11,700 km per year or 32.0 km per day [45] which is the default value for this variable. This variable affects all model outputs. The energy required to charge the vehicles is directly attributed to the km per day where the total daily energy needed for the EV is the km traveled multiplied by the average energy used per km for the EV.

5.6. Home energy storage

This variable specifies the total kWh of the battery pack installed at the household. The battery pack can store energy generated from either the solar PV system or from the grid (e.g. at low-price times, according to the tariff type). Larger battery storage will allow for more excess solar energy to be shifted to a time when no solar energy is produced. In Australia this is important because the cost of buying electricity per kWh is significantly higher than the revenue generated from selling it back to the grid. Therefore is preferable to retain the energy and reduce the energy purchased from the grid, rather than offsetting energy purchased from the grid by selling generated energy back to the grid. This variable affects the energy amounts as well as annual cost and savings.

5.7. Household consumption

This variable defines the average household energy consumption per day excluding any EVs. The household power usage for Western Australia was collected by Western Power in a study on the impact of photovoltaic generation on peak demand as 16 kWh per day [46].

5.8. Tariff type

Consumers in Western Australia can choose between different electricity tariffs. For the average household these can be simplified to two plans, flat tariff and time-of-use tariff. A flat tariff charges the same dollar amount per kWh irrespective of the time of day. The time-of-use tariff in WA distinguishes between peak, off peak and shoulder times with different power pricing.

Our energy planning tool show the amount of energy used and the cost associated with either flat or time-of-use tariff, based on the tariffs available from WA electricity retailer Synergy at the time of the WA Electric Vehicle Trial [47]. The time-of-use tariff has peak, off-peak, and shoulder segments, which change between summer and winter season. The cost of electricity during an off-peak period is 11.32 cents/kWh, peak is 42.15 cents/kWh and shoulder is 21.44 cents/kWh. This contrasts to the flat tariff cost of 26 cents/kWh. The winter months in Australia are April to September and summer months are October to March. Fig. 7 shows the summer and winter plan times.

When using a time-of-use tariff, the model gives the option to charge from the grid during off-peak times. Also Erdinc Et Al. [48] showed that there are significant changes in normal consumption patterns by changes to electricity prices.

6. Adding local energy generation and local energy storage

Following the model presented earlier, we are now using our online tool, available at:

http://therevproject.com/energy/

for finding a step-by-step solution to add the ideal amount of energy generation and energy storage to a local household.

We start with a typical household, as identified in Western Power's Solar City survey [46]. The typical daily power consumption for a household is 16 kWh with a smaller peak in the morning and a larger peak in the evening.

Adding renewables in the form of solar PV is usually the next step for a household, trying to reduce their power bills. Fig. 8 shows adding a moderate amount of 2 kW peak. This generates an annual savings of $573 with the current Synergy energy plan.

Solar PVs alone cannot completely cover a household's energy needs. They will offset all of the energy requirements during sunshine hours and further allow some feed-in to the grid. This generates some income, which can be used to offset the energy cost from the grid during evening, night and morning hours of the day.

Adding more solar PC to the household, as is shown in Fig. 10, will not lead to any further reduction in energy required from the grid, as all the remaining demand is outside of sunshine hours. It does, however, increase the amount of energy that can be exported to the grid (feed-in), if there is a grid connection and the network operator is in fact accepting the feed-in energy. In this case the energy fed into the grid generates $505 annually and combined with the reduced amount of power bought from the grid during daylight hours, a household can save AUD 1040 per year.

Also note that the amount of solar energy generated from e.g. a 1 kW peak system varies especially with country and region, plus a number of additional factors. Typically a 1 kW peak systems generates 1.6 MWh of energy in Western Australia, but only 0.8 kWh in Germany.

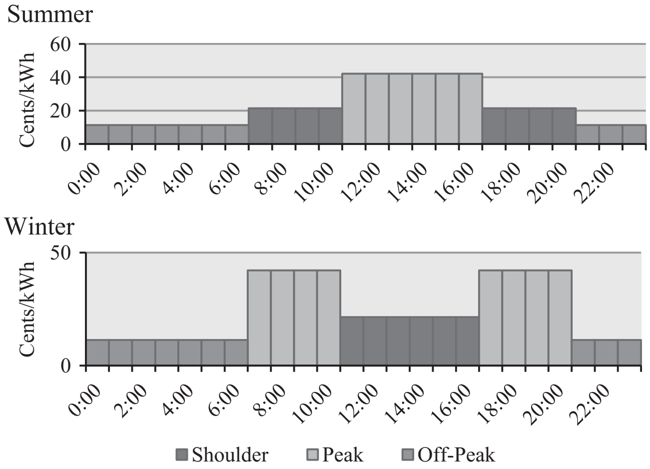


Fig. 7. Summer and winter tariffed plans from Synergy Australia, 2013.

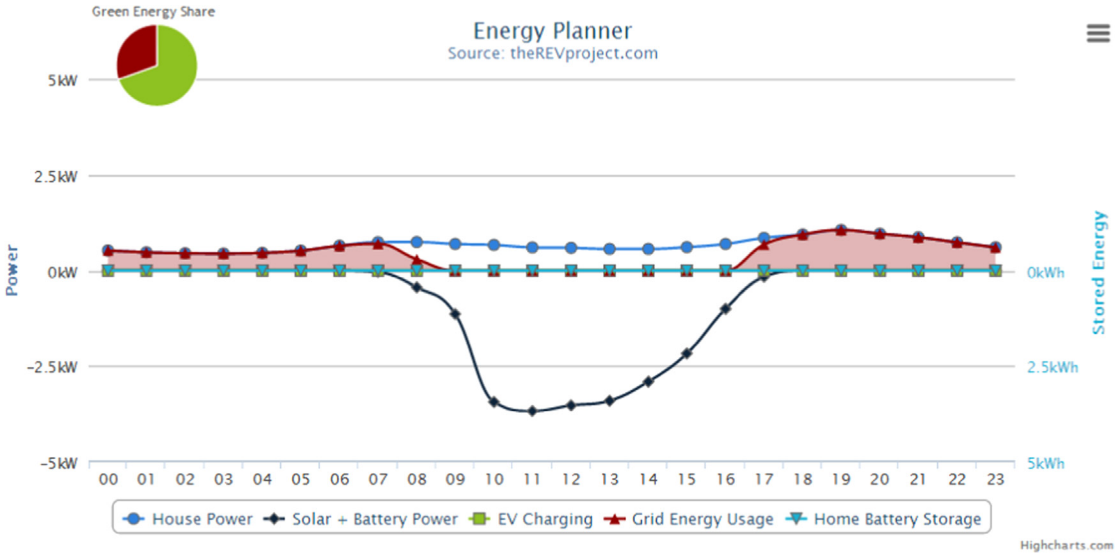


Fig. 8. Household with 5 kW peak solar PV.

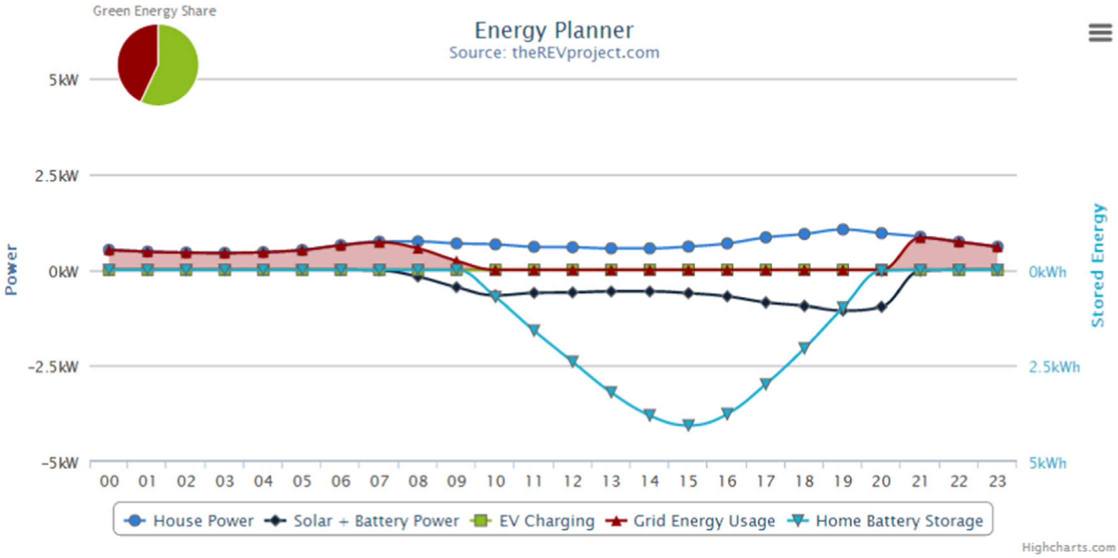


Fig. 9. Household with a moderate amount of solar PV.

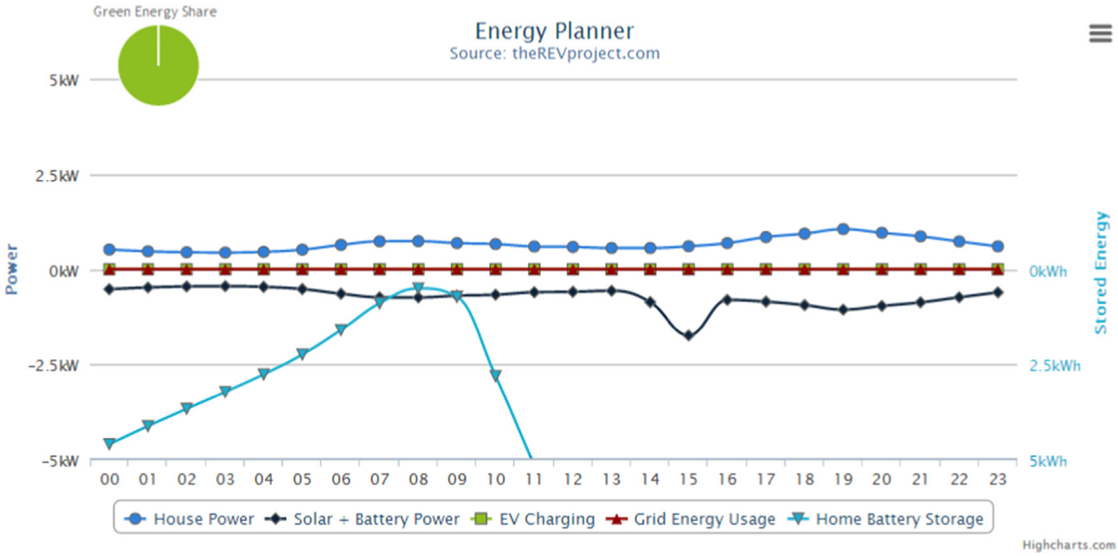


Fig. 10. Household with 4 kW peak solar PV and 11 kWh battery storage.

The next step is adding some moderate amount of local energy storage as seen in Fig. 9. With a small 2 kW solar PV and a 5 kW energy storage, annual savings will increase from $573 to $832. By adapting the slide rulers of our online tool, one can find the optimal amount to cover all energy usage of the displayed ‘average day’, see Fig. 10. The tool also allows for automatic calculation of the optimal solar and battery system with a optimize button. There are many different techniques researched for optimizing energy generation and storage [49], such as Hybrid Optimization Model for Electric renewable (HOMER) [50] and Hybrid Optimization by Genetic Algorithms (iHOGA) [51], while the technique used in this software optimizes for one day. This requires a 4 kW solar PV system and an 11 kW energy storage system. Such a system will save a household AUD 1565 of electricity cost per year and will not require any power from the grid (not considering days with exceptional weather conditions as described in Chapter 4).

Optimizing energy generation and storage for the ‘average day’ lets us find the most cost-effective energy generation and storage solution for homes that have a grid connection with moderate connection fees. Off-grid solutions require a significant energy buffer in order to cope with ‘non-average’ days (in fact, they have to cater for the days with highest energy consumption, e.g. hottest/coldest days of the year to allow electric air-conditioning or heating) and they have to allow for a number of hazy days in a row with very little solar PV generation (typically 3–5 days). As shown for the Future Farm, the overall household energy consumption must stay within the design parameters of the solar PV and battery system or batteries may run flat and the household will be without power until the next day when the solar PV is generating again.

This makes the energy storage required for an off-grid solution significantly larger and more expensive. The alternative here is to use battery energy storage only for the ‘average day’ or provide alternative energy generation, such as a Diesel generator for backup purposes.

When using a time-of-use tariff, it is also possible to charge the energy storage at cheaper off-peak times for use during expensive on-peak times. This is shown in Fig. 11 for a 10 kWh battery storage and no solar PV. It will save the household AUD 622 per year. It is important to note that battery storage systems are not allowed to feed power back into the grid under Australian law.

7. Adding electric vehicle charging

We expect Electric Vehicles to be the transportation medium of the future and a large proportion of the energy required for driving energy will be provided through home charging. So how will the energy balance change, if we add one or two electric vehicles to the equation?

Fig. 12 shows the additional energy requirements with one EV and the typical urban distance driven of 32 km per day (about 12,000 km per year). Additional energy generation and storage capacity are required, in order to cover this significant additional demand. This has been done in Fig. 13, where we now have installed a 6 kW peak solar and 14 kWh storage. Additional EVs can be added and the energy parameters be adjusted accordingly.

Please note that we do not consider ‘vehicle-to-grid’ (V2G) technologies or even vehicle-to-home. Mullan et al. [52] have shown quite clearly that V2G schemes are not economical in the sense that the wear and tear on EV batteries (based on today's Lithium technology) can never be repaid by any reasonable energy tariff. EV batteries have been designed to last for the lifetime of a car, which is typically set to about 10 years or 36,500 charge/discharge cycles when using the car on a daily basis. After this, the battery will typically have a reduced capacity of 85% and the EV an equally reduced driving range. This is considered no longer adequate for driving, but the battery may well be used for stationary energy storage purposes. Under normal conditions, the lifetime of an EV battery is large determined by the number of charge/discharge cycles it undergoes. V2G would now effectively double the number of cycles per day, so the EVs battery would become obsolete after five years and the EV owner would be up for a bill in the order of AUD 15,000. The only gain for V2G was temporarily storing a small amount of energy per vehicle, e.g. around 5–10 kWh, so the cost (or damage) created though V2G is in the order of AUD 8.22 per charge cycle or more than AUD 1.00 per kWh, which is a multiple of current energy prices.

Although V2G seems not economically viable today, the situation may change in the next couple of decades, in case new battery chemistries with a longer lifetime are developed that can endure a larger number of charge/discharge cycles.

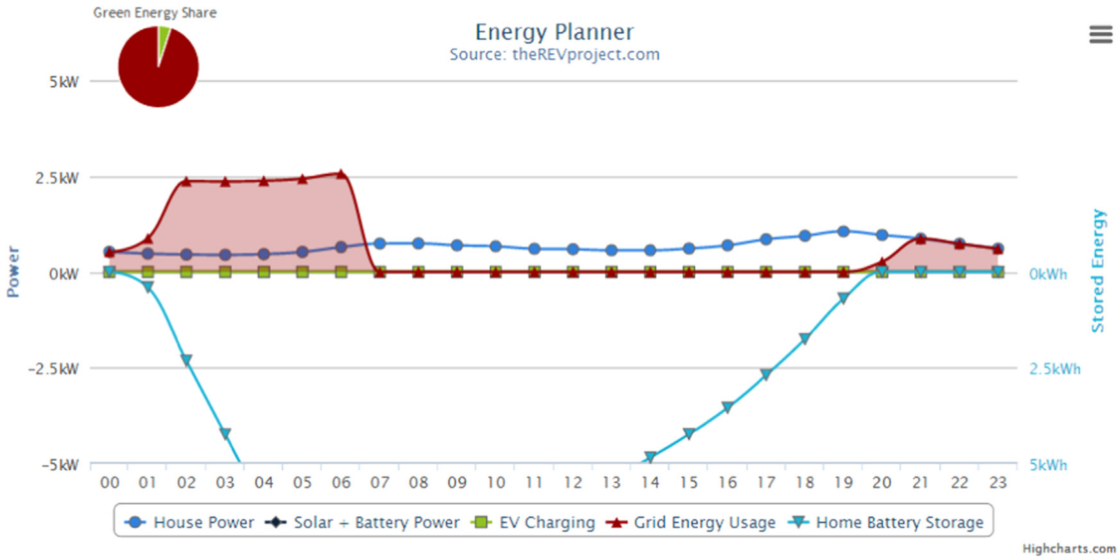


Fig. 11. Household with 4 kW peak solar PV and 11 kWh battery storage.

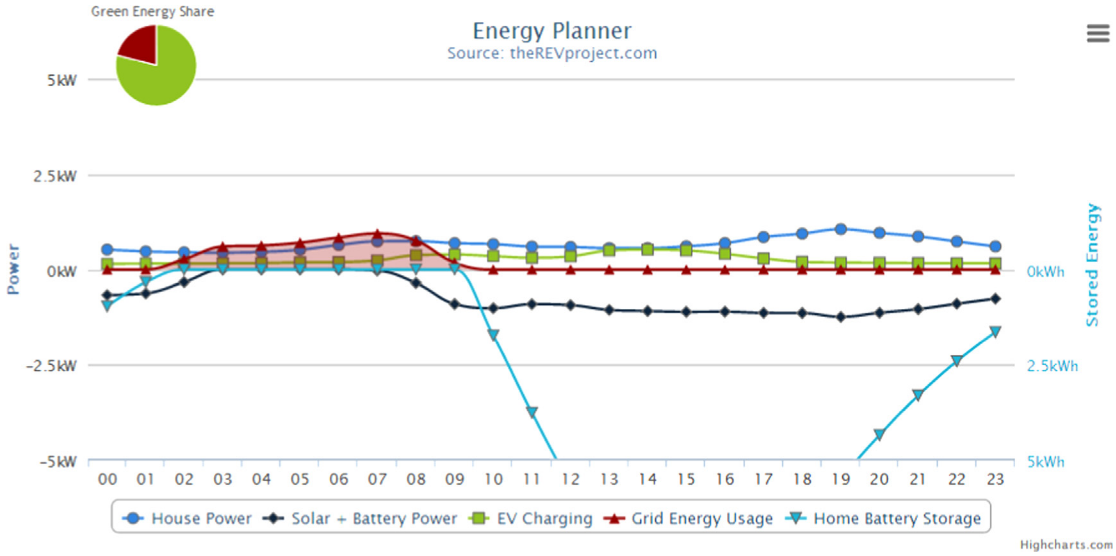


Fig. 12. Household with one electric vehicle.

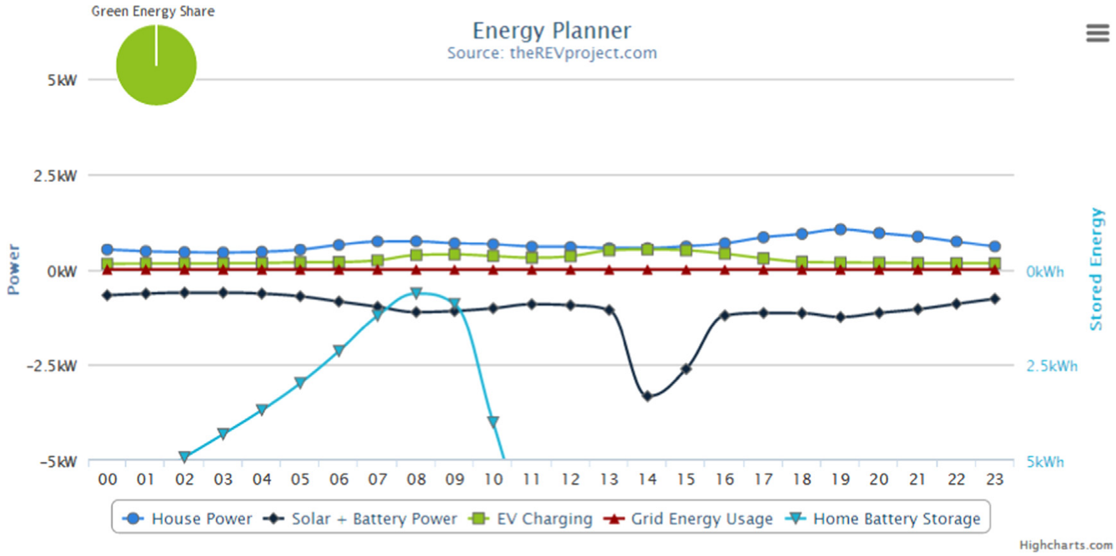


Fig. 13. Household with one EV and increased solar PV and battery storage to match higher energy requirements.

8. Conclusion

Going off the grid poses considerable design considerations and challenges. Electricity is required to be available on demand and reliably to support modern living.

The technology available at the moment makes a solar PV system with Lithium Ion batteries the most feasible option.

Extended power outage times due to batteries running flat are not acceptable. When designing an off-grid solution with renewable technologies it is necessary to over-dimension the system with a margin to ensure that the power is available even in rare weather conditions. This leads to considerable additional expenses and a generally under-utilized PV, as energy supply will on average far exceed demand. UWA's Future Farm only had a solar PV utilization of 40% and still experienced occasional power outages due to high energy usage after a series of days with low solar PV generation. A combination of solar PV and battery storage with grid connection or backup diesel generator allows for extreme scenarios with renewable energy being used for 'average days'. Also, being able to feed-in surplus energy to the grid allows a much more cost-effective solution. It is important to note that grid feedback may not be available for some rural areas or industry, and in other cases it may be available but there is no financial benefit.

Off-grid solar PV and battery systems are also very inflexible to utilization changes, e.g. if the household grows and requires more energy than its original design. When UWA's Future Farm had two air-conditioners installed for heating during the night, the demand more than doubled from the original 17 kWh per day to 36 kWh per day leading to the power running out at several occasions of extreme weather conditions.

Data on average household power demand versus typical solar PV curves demonstrate that there is a need for shifting energy from midday to the later hours in the day, and battery storage systems can provide a solution for this at a household level. The adoption of battery storage systems will depend on the development of future energy prices, feed-in tariffs for solar PV and possible energy storage subsidies.

For the average Australian household consuming 16 kWh daily with modeling we show that their entire power usage can be offset by a 4 kW PV system and an 11 kWh battery.

References

[1] (Germany), F.N.A., EEG feed-in tariffs Oktober until December 2014, F.N.A. (Germany), Editor. 2014, Federal Network Agency (Germany): ⟨http://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/ErneuerbareEnergien/Photovoltaik/Datenmeldungen/EEG_Saetze_Okt-Dez.xls?__blob=publicationFile&v=1⟩.
[2] Europes Energy Portal; 2013 [cited 11.09.13].
[3] Synergy. Renewable energy buyback scheme and net feed-in tariff price schedule; 2013.
[4] Synergy. Standard electricity prices and charges; 2013.
[5] Australia S. SMA integrated storage system; 2013. Available from: ⟨http://www.sma.de/en/solutions/medium-power-solutions/sma-smart-home/turn-key-storage-solution.html⟩.
[6] Mohammed YS, Mustafa MW, Bashir N. Hybrid renewable energy systems for off-grid electric power: review of substantial issues. Renew Sustain Energy Rev 2014;35(0):527–39.
[7] Ecoult. Australian government investment supports big thinking on small-scale energy storage; 2013.
[8] Freris L, Infield D. Renewable energy in power systems. John Wiley and Sons; 2008.
[9] Bhandari B, et al. A novel off-grid hybrid power system comprised of solar photovoltaic, wind, and hydro energy sources. Appl Energy 2014;133(0):236–42.
[10] Harries D. Average annual solar production in Western Australia. In: Speidel S, editor. EMC Solar; 2013.
[11] Choice S. Solar PV price index–June 2013; 2013 [cited 5.08.13]. Available from: ⟨http://www.solarchoice.net.au/blog/solar-pv-price-check-june-2013/⟩.
[12] Hernandez J, Gordillo G, Vallejo W. Predicting the behavior of a grid-connected photovoltaic system from measurements of solar radiation and ambient temperature. Appl Energy 2013;104(0):527–37.
[13] Dopita M, Williamson R. Australia's renewable energy future. Australian Academy of Science; 2009.
[14] Jeanes T. Wind farms churn out more than half SA's electricity during wild weather; 2013.
[15] Mithraratne N. Roof-top wind turbines for microgeneration in urban houses in New Zealand. Energy Build. 2009;41(10):1013–8.
[16] Alam F, et al. Status of power generation by domestic scale wind turbines in Australia. Proc Eng 2012;49(0):205–12.
[17] Trust ES. Location, location, location: domestic small-scale wind field trial report; 2009.
[18] Climate statistics for Australian locations. Editor, Bureau of Meterology; 2013.
[19] Sunderland K, et al. Small wind turbines in turbulent (urban) environments: a consideration of normal and Weibull distributions for power prediction. J Wind Eng Ind Aerodyn 2013;121(0):70–81.
[20] Coppin PK, Ayotte KA, Steggel N. Wind resource assessment in Australia: a planners guide; 2003.
[21] BlueGen. BlueGen; 2013 [cited 11.09.13]. Available from: ⟨http://www.bluegen.info/⟩.
[22] Wang Y, et al. Modelling and simulation of a distributed power generation system with energy storage to meet dynamic household electricity demand. Appl Therm Eng 2013;50(1):523–35.
[23] Xiaonan W, Palazoglu A, El-Farra NH. Operation of residential hybrid renewable energy systems: integrating forecasting, optimization and demand response. In: Proceedings of the American control conference (ACC); 2014.
[24] Underwood CP, et al. Renewable-energy clusters for remote communities. Appl Energy 2007;84(6):579–98.
[25] Parra D, et al. Optimum community energy storage system for PV energy time-shift. Appl Energy 2015;137(0):576–87.
[26] Goldfinch I. Home energy storage. In: Speidel S editor; 2013.
[27] Reddy T. Linden's handbook of batteries. 4th EditionMcgraw-hill; 2010.
[28] Buchmann I. Charging the lead-acid battery; 2013 [cited 14.08.13] Available from: ⟨http://www.idl.ku.edu/ARA/AARPS/Documents/Batteries&Chargers/Battery_U_13_Charging.pdf⟩.
[29] Papazov G, Pavlov D. Influence of cycling current and power profiles on the cycle life of lead/acid batteries. J Power Sources 1996;62(2):193–9.
[30] Maclay JD, Brouwer J, Scott Samuelsen G. Dynamic analyses of regenerative fuel cell power for potential use in renewable residential applications. Int J Hydrogen Energy 2006;31(8):994–1009.
[31] What's the best battery? [cited 11.08.13]. Available from: ⟨http://batteryuniversity.com/learn/article/whats_the_best_battery⟩; 2013.
[32] Rincón-Mora GA. Analog IC design with low-dropout regulators (LDOs). The McGraw-Hill Companies, Inc; 2009.
[33] Sky T. Thunder sky lithium ion battery specifications model TS-LFP200AHA; 2012.
[34] Hall PJ, Bain EJ. Energy-storage technologies and electricity generation. Energy Policy 2008;36(12):4352–5.
[35] Beaty HW, Fink DG. Standard handbook for electrical engineers, 16th ed. The McGraw-Hill Companies, Inc; 2013.
[36] Ibrahim H, Ilinca A, Perron J. Energy storage systems—characteristics and comparisons. Renew Sustain Energy Rev 2008;12(5):1221–50.
[37] Wang C, Nehrir MH. Power management of a stand-alone wind/photovoltaic/fuel cell energy system. IEEE Trans Energy Convers 2008;23(3):957–67.
[38] Rydh CJ, Sandén BA. Energy analysis of batteries in photovoltaic systems. Part I: performance and energy requirements. Energy Convers Manag 2005;46(11–12):1957–79.
[39] Tong SJ, et al. Off-grid photovoltaic vehicle charge using second life lithium batteries: an experimental and numerical investigation. Appl Energy 2013;104(0):740–50.
[40] Inman RH, Pedro HTC, Coimbra CFM. Solar forecasting methods for renewable energy integration. Prog Energy Combust Sci 2013;39(6):535–76.
[41] Mellit A, Kalogirou SA. Artificial intelligence techniques for photovoltaic applications: a review. Prog Energy Combust Sci 2008;34(5):574–632.
[42] Richardson DB. Electric vehicles and the electric grid: a review of modeling approaches, impacts, and renewable energy integration. Renew Sustain Energy Rev 2013;19(0):247–54.
[43] Stuart Speidel FJ, Olaru Doina, Harries David, Bräunl Thomas. Analysis of Western Australian electric vehicle and charging station trials. Aust Transp Res Forum 2012.
[44] Mader T, Bräunl T. Western Australian electric vehicle trial 2010–2012; 2013.
[45] ABS, Survey of motor vehicle use, A.B.o. Statistics, editor; 2011.
[46] Western_Power. Study on the impact of photovoltaic generation on peak demand, Western_Power, editor; 2012.
[47] Synergy. ⟨https://www.synergy.net.au/docs/Standard_Electricity_Prices_Charges_brochure_MSF.pdf⟩; 2013.
[48] Erdinc O, et al. A new perspective for sizing of distributed generation and energy storage for smart households under demand response. Appl Energy 2015;143(0):26–37.
[49] Erdinc O, Uzunoglu M. Optimum design of hybrid renewable energy systems: overview of different approaches. Renew Sustain Energy Rev 2012;16(3):1412–25.
[50] Homer Energy [cited 12.11.14]. Available from: ⟨http://homerenergy.com/⟩; 2014.
[51] López DRD. General information iHOGA. [cited 12.11.14]. Available from: ⟨http://personal.unizar.es/rdufo/index.php?option=com_content&view=article&id=2&Itemid=105&lang=en⟩; 2014.
[52] Mullan J, et al. The technical, economic and commercial viability of the vehicle-to-grid concept. Energy Policy 2012;48:394–406.

Stuart Speidel is a Ph.D. candidate at The University of Western Australia (UWA), Perth where he manages the Renewable Energy Vehicle (REV) project, having monitored a fleet of road licensed EVs and their interaction with charging stations. He is under an ARC Linkage grant scholarship to manage and track the Electric Vehicle Fast Charging Network. He holds a bachelor or engineering in Software Engineering from Curtin University, Western Australia.

Thomas Bräunl is a professor at The University of Western Australia, Perth, where he directs the Renewable Energy Vehicle Project (REV), having converted several road licensed cars to battery-electric drive. He is Technical Director of the West Australian Electric Vehicle Trial and the Principal Investigator of the ARC Electric Vehicle Fast-Recharging Project. He has worked on Driver-Assistance Systems with Daimler and on Electric Vehicle Charging Systems with BMW. Professor Bräunl holds a Diploma from Univ. Kaiserslautern, Germany, a M.S. from USC, Los Angeles, and a Ph.D. and Habilitation from Univ. Stuttgart.

REView – An Internet Portal for Monitoring Electric Vehicles and Charging Stations

Stuart Speidel
Norwood Systems
Perth, Australia
stuart.speidel@norwoodsystems.com

Thomas Bräunl
The University of Western Australia, EECE
Perth, Australia
Thomas.Braunl@IEEE.org

Abstract—**REView is a software suite to automatically collect, analyze, and review live and recorded data from electric vehicles (EVs) as well as EV charging stations. The data described in this paper has been collected live from the Western Australian Electric Vehicle Trial and the WA Charging Station Trial. A secure web portal was designed with different viewing portals for electric vehicle users, charging station users and charging station owners. It includes informative statistics about a user's driving efficiency and energy use, compared to the average of all other users. It further includes a smartphone application for live monitoring, and itemized billing. In this paper, we discuss the development of the REView software suite, including mechanisms used to generate and collect the information. Finally, we show and discuss the data itself and the lessons learned from it. This information includes the charging time, duration, energy used, as well as utilization metrics of the charging infrastructure.**

We promote an open source approach to charging station software development. This will allow a single software backend to handle multiple stations from different manufacturers, promoting competition and streamlining the integration of charging technologies into other devices.

Keywords—EV, Electric Vehicle, Charging Station, Tracking, Monitoring, Web Portal, Charging Statistics

I. INTRODUCTION

Being able to collect individual user data for Electric Vehicles (EVs) and EVSEs (electric vehicle supply equipment, "charging stations") and relay them back to the user in both itemized and statistical form provides a substantial added value for individual mobility.

The REView portal is a web-based software package that collects individual user data from electric vehicle trackers, charging station monitors and renewable energy data loggers. It then performs automatic statistical evaluations and presents the results to users in a meaningful and informative way, letting each user know about his or her own individual mobility costs, as well as their ranking in the community of other EV users of this software suite. We find that by illuminating the user's patterns and contrasting it with data from other users, we can motivate individuals to reduce their energy consumption and carbon emissions, as well as, in general, educate people about zero emission transportation. The approach of competing users against each other is known as *gamification* and has already been used in related areas [20].

The statistics generated allow drivers and fleet managers to monitor their vehicles' efficiency and energy use. It allows charging network operators to monitor the effectiveness and usage of their stations, and it allows station users to monitor their energy usage and costs. This information is made available in several ways, including live mobile phone web applications, desktop web applications, data exporting and printing.

REView was developed as part of two different projects:

1. The Western Australian Electric Vehicle Trial, Australia's first EV trial, consisting of eleven locally converted EVs based on Ford Focus, owned by various businesses and government agencies [1].
2. The installation of the Western Australian charging station network, a set of 23 AC and one DC Electric Vehicle charging outlets, which are made available to the public. At the time of print, this constitutes one of the largest charging station networks in all of Australia.

REView has helped in analyzing driving and charging behaviors of EV drivers [21, 22, 23] and statistics generated from this system has been used in setting up an acceptance study among EV drivers [24].

REView is currently providing real-time monitoring of vehicles, charging stations and solar installations around Western Australia, with new statistics generated every half hour. The software is a combination of Python servers, Cron batch scripting of Python for statistical processing, PHP server side and PostgreSQL backend with JavaScript, CSS and HTML for the user interface. Because these open source languages (along with several open source libraries) make up the system, it has the ability to be widespread and available to any educational or not-for-profit organization. We hope this will promote further research into charging station infrastructure and show that it is possible to fill the void between a research organization's need for data collection and the government/corporate sponsors' need for investment return.

Throughout the development of this software there were several lessons learned on stakeholders, requirements, feature acceptance by station users, and general possibilities for charging station software. We believe that the features that were developed in this system help form a baseline for future vehicle tracking and charging station monitoring software developments. Through the EV Trial we found that commercial software which is sold bundled with charging stations often lacks vital functions and can be very awkward to operate. Also in all cases we have seen, such software is limited to the associated company's charging hardware, not supporting interoperability with other stations. With many different charging station manufactures, this makes management, analysis and billing troublesome.

II. Local and International Adoption Of Electric Vehicles and Charging Stations

Before the WA EV Trial and the charging station trial, there were no OEM-built (commercially built) EVs available in Australia and no charging stations in Western Australia. Since then, several manufacturers have released new electric vehicles and plug-in hybrid vehicles into the Australian market, including Mitsubishi, Nissan, Holden, BMW, Porsche and Tesla Motors. The 2013 Frankfurt Motor Show IAA was "dominated by electric vehicles" according to its media coverage [2]. Globally the number of Electric Vehicles has grown from 700,000 in 2014 to 1.26 million in 2015 [3]. Electric vehicles are no longer a dream, but a reality, and every year we will see more on our roads. For fleet managers, tracking and logging of energy usage, as well as localization and utilization are valuable tools to reduce carbon emissions and expenses.

Meanwhile the number of charging station manufacturers has increased dramatically, and many governments around the world are subsidizing their installation to meet the desire to reduce the dependence on oil. While charging station manufacturers currently have incompatible customer identification methods and competing management software, the Open Charge Point Protocol (OCPP) [4] has been introduced as a possible new standard for EVSE communication. OCPP is an open, uniform communications protocol that can be used across all charging stations. Already, many manufacturers are supporting this protocol – now being the most popular protocol for new stations. This means that external companies can access the data and control of the stations via an Application Program Interface (API), no matter which manufacturer.

The number of EVs in Perth, Western Australia, has grown from 15 in 2010 to over 100 in 2015 and every year it is projected to grow. Various consulting firms and governments have forecasted the growth of EV sales in Australia. In 2009 the Department of Environment and Climate Change commissioned consulting firm AECOM to study the economic viability of electric vehicles [5] and they projected that supply constraints would limit the sales of EVs (including hybrids) in Australia until 2020 and in each of their three projections over 60% of new cars would be plug-in hybrids or pure EVs by 2040. AECOM released another report in 2011 for the Victorian Department of Transport where through the use of a vehicle choice model they concluded that sales of hybrid electric vehicles in Victoria will be more predominant in the short term, (up to 5 years), plug in electric vehicles in the medium term (5-10 years) and EVs in the long term (15 years plus) [6]. They also found evidence that high levels of charging infrastructure will significantly increase the adoption of EVs.

In 2012, ABMARC performed a survey of motorists in Australia with a conservative estimate of EV uptake. They concluded that without a breakthrough in battery technology the adoption of EVs by 2020 would likely be 0.4% of new car sales [7]. However, plug-in hybrid electric vehicles would constitute a much large proportion of 6.4% of the new vehicle market.

The Energy Supply Association of Australia reviewed several different forecasts for Australia, showing that they all had several factors in common that controlled EV uptake, with a major factor being available EV charging infrastructure [8].

III. Importance of measuring evironmental impact

The environmental impact of running any vehicle needs to be analyzed from its source. The environmental benefit in terms of CO_2 emissions of EVs relies quite heavily on the way the electricity is generated. From 2014 to 2015 94.2% of all electricity generated came from non-renewable resources, with 32.2% from coal, 73.8% from oil and 24.2% from gas [9]. The Union of Concerned Scientists released a report in 2012 stating that how the electricity was generated directly affects the environmental benefit of a Nissan Leaf in the US [10]. Their report showed that in some regions the difference in carbon emissions in electricity generation varied as much as three times, where a nuclear and renewable energy mix of generation is compared to a heavier coal and gas driven power generation. This meant that vehicles in areas with high electricity emissions were comparable to highly efficient petrol vehicles (17% of all Americans live in these areas).

TABLE I. Efficiency and Theoretical Emissions of Electric Vehicles

Model (* is PHEV)	**Efficiency (Wh/km)**	**Range (km)**	**CO_2 (g/km)**
Mitsubishi i-MiEV	135	150	126
Nissan ZE0 Leaf	173	175	162
Renault Kangoo ZE	155	170	145
Tesla Model S	181	390	169
Holden Volt*	135	87	126
Mitsubishi Outlander*	134	52	125
Porsche Panamera SE*	162	36	152

Model, kWh/km and range from greenvehicleguide.gov.au [12],
CO_2 emission calculated from SMEC 2008.

A report by SMEC in 2008 for the Department of Transport states that in Western Australia the amount of $kgCO_2$ Emissions per kWh is 0.936 [11]. From this information and the efficiencies of the models from the Australian Department of Infrastructure and Regional Development [12] one could calculate theoretical CO_2 emissions per km of the EV available in WA. However, this would assume that these cars are charged entirely from the average grid without any renewables, which is clearly not the case. Many early EV adopters also have solar PV generation at home and are able to charge their cars completely emission free. Also, the focus on CO_2 values misses more harmful emissions, such as carbon monoxide and particulate matter, which can be much better controlled in power stations than in combustion engine cars.

In 2013, the Australian National Transport Commission released a report discussing the carbon dioxide emissions of new Australian Vehicles [13]. They found that the average g CO_2 per km was 199g/km, meaning that EVs in the worst case scenario generate less emissions than the average new petrol car. To reduce or remove CO_2 emissions for EVs, they must be charged (or arguably offset) from a renewable energy resource.

It is important to note that air quality in metropolitan areas will improve through the use of EVs, even when charged from a "dirty grid". EVs produce zero tailpipe emissions and power stations are typically located in less populated areas outside a city. Also, many emissions can be better dealt with at a power station than at thousands of ICE (internal combustion engine) cars.

IV. INFRASTURUCTURE

Here we discuss the EVSE, EV and renewable energy sources that are currently monitored by REView. All of these technologies use their own software interfaces and integration.

A. *Charging Station Infrastructure*

The charging stations currently installed in Western Australia had been sourced from the United Kingdom, built by charging station company Elektromotive. In the absence of an Australian standard, we selected the European standard IEC 62196 Type-2 (Mennekes) connectors for Level-2 charging at 7.7kW, which unlike the US/Japan standard Type-1 (J1772) does support charging using three-phase power, which is prevalent in Australia, but not in the U.S. The stations are water resistant and fitted with overcurrent protection and RCD switches.

In terms of compatibility, there are at least five different types of connectors for the charging EVs in WA:

- Standard Australian household socket (10 and 15A) - AS/NZS 3112
- Standard Australian 3-Phase socket (20A and 32A)
- IEC 62196 Type-1 ("SAE J1772")
- IEC 62196 Type-2 ("Mennekes")
- Tesla's AC/DC variation of IEC 62196 Type-2
- CHAdeMO (Japan)
- Combo CCS/Type-1 (Combined Charging System, IEC Type-1 variant "SAE")

Most manufacturers (Mitsubishi, Nissan, BMW and Porsche) are now releasing their cars with a Type-1 standard in the Australian market, only Tesla uses IEC Type-2.

Charging station users have been supplied with RFID tags for identification, to allow monitoring and future billing. This also reduces the risk of cable theft, as only the correct tag can release the charging cable. Other identification methods used elsewhere include smartphone login, credit card swipe and in-vehicle identification, but these require higher security standards (in case of credit card readers) and constant internet connection, which makes these methods more expensive.

B. *EV Monitoring*

We use GSM-based tracking devices from Astra Telematics, models AT100 and AT240 GPS for vehicle data logging. These tracking devices communicate with the REView server via an internal GSM modem, using a SIM card with machine-to-machine (M2M) capabilities. The five digital input lines of the tracking devices are connected to the air conditioning, ignition, headlights, radio and heater statuses. The analog input line is connected to a battery level logging device that outputs the battery level percentage as an analog voltage. The battery meter counts the energy flowing in and out of the main electric vehicle battery pack using a ct current sensor.

C. *Solar Photovoltaic Monitoring*

Fig. 1. A 20kW solar system on the Human Movement building of UWA, Western Australia

D. *Solar Tracking Features*

We monitor a roof-top solar PV system of 20kWp, installed on UWA's Human Movement building. For data collection, a Sunny Webbox is used in conjunction with the solar inverters. This allows logging and downloading of energy data every minute via ftp.

V. REVIEW SOFTWARE DESIGN

A. *REView System Design*

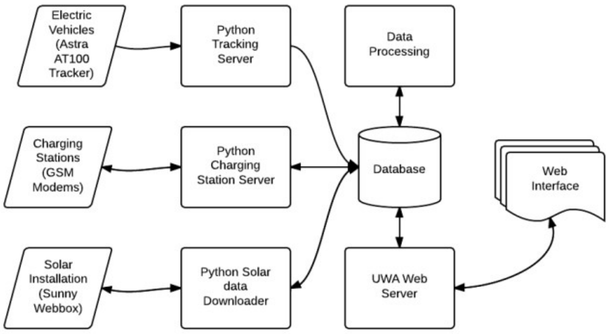


Fig. 2. Software system for the REView server

The system consists of seven components and is configured as shown in the image above:

1. Electric Vehicle Server
2. Charging Station Server
3. Solar Downloader
4. Data Processing Scripts
5. Database
6. UWA Web Server
7. Web Interface

In this section, we will go into detail for the EV server, charging station server, solar data downloader and batch data processing. The database is a PostgreSQL, the web server is Apache, and the interface is further discussed in section VII.

B. Electric Vehicle Server

The charging system monitoring is done with a Python daemon running the Threading Socket server library. This library listens for TCP connections on a defined port and creates a new thread for each one, which can handle the processing of the data received. The processing is done by parsing the incoming message from the byte stream into Python variables, connecting to the database and inserting the new data points.

The following information is recorded in a PostgreSQL database for each data point: latitude, longitude, time logged on device, time received at server, vehicle speed, vehicle heading, altitude, journey max speed, journey max acceleration, journey distance, journey idle time, ignition status, alarm line status (unused), air conditioning status, headlights status, heater status, charging status, and car battery level. The GPS positions and line inputs are uploaded onto the server either at every minute or at every ten meters, whichever comes first. This raw data is later processed and combined with other data by batch scripts into more useful information.

C. Charging Station Server

The charging station server also uses a Python daemon, similar to the electric vehicle server. This server, however, does not just receive information from the stations but also checks and sets the stations' real time clock, and requests information from the stations' internal database. The charging station modems are configured to connect to the server, allowing them to use dynamically allocated IP addresses, which are generally a cheaper option to using more convenient static IPs.

The station server requests the status every five minutes, which includes the number of events that have occurred at the station, the current status (charging, idle, error), the energy drawn for the latest charge event, the total energy supplied over all time, real-time clock and latest user id (if in use). This information is recorded in the servers' database.

The station has a record of several different types of events, including charging, disconnect, power failure and reset. When the number of recorded events at the server is less than that at the station, the excess records are downloaded and stored for later statistical analysis.

The configuration of a station is done using proprietary software. The stations allow the configuration of several parameters, including the minimum and maximum power outputs and charge time restrictions. It also gives the administrator the ability to remotely login to the station or disconnect a user, or reset a station. To allow this software to connect to the station the server can open an SSH tunnel between the station and the administrator PC. This can be used to either remotely configure the station's GSM modem or the charging station itself.

D. Solar System Download

The solar system download uses a Python batch script run as a "Cron" job on the server. This script will scan through a list of remote FTP addresses, access an expected file structure, download new or updated CSV files on that remote device, and parse them into the database. The data from the solar system includes time stamps, power generated, voltages at the panels and grid and operation health flags.

Solar systems are connected to and scanned every 15 minutes for data download.

E. Data Processing Scripts

The information that comes into the database from the servers is raw telemetry, charging station data and solar energy data. Data pre-processing is used for speeding up the delivery of statistics graphs to the user, which is important for usability and scalability. Data processing is done by several Python scripts that look for changes in the raw data, to create new data sets. An example of one of these processes is creating journey events from raw telemetry data. When a vehicle is detected and its ignition status changes from on to off, then the script looks backwards from that point to form a journey. The data is combined into meaningful fields such as total distance travelled and energy used.

The Python scripts are scheduled as a Cron job on the server, activating every 30 minutes. The scripts perform the following:

- Generate vehicle journeys, charging events, idle events, missing data events
- Generate charging station events
- Combine similar charging station and vehicle charging events based on user tag, time and location
- Compress data, such as air conditioning, heater, headlights into a data point for a journey
- Compress charging data into charging/maintaining charge, divide into by-hour and by-week arrays
- Generate heat maps

As separate scripts are used for different functions, adding new functionality or statistics can be easily done by adding an additional script. This limits the need for modifying existing software and reduces integration problems and helps in isolating errors.

VI. SIMILAR TECHNOLOGIES

A. Commerical Technologies for EV tracking

There are several examples of commercial GPS tracking software packages for fleet vehicles. Commercial vehicle tracking is used in many different industries including mining, trades, utilities, transportation, and government agencies. There are several different products available in

Australia, such as EZY2C [14], Fleetmatics [15] and ReadyTrack [16]. These products claim to provide solutions that will reduce fuel costs, improve productivity, reduce labor costs, and increase accurate reporting. These services install GPS tracking devices into the fleet vehicles to monitor them remotely. The major drawback of such commercial systems is that they don't record energy usage or the status of charging, air conditioning, heating and headlights but rather exclusively rely on a GPS unit. Additionally, they don't include information from other devices, such as charging infrastructure All these systems aim at the petrol fleet market.

B. Research Topics

Many institutions around the world have started research into tracking and monitoring of electric vehicles and charging stations, using their own GPS systems and charging infrastructure. In the North East of England, Blythe performed a study tracking 15 electric vehicles and a charging station network [17]. They concluded with stating their ability to use the data from tracked vehicles to derive the state of the charging station network. From there they are able to predict possible future problem areas for electricity power generation.

Fig. 3. Tracking page for the REView software

VII. REVIEW FEATURES

The REView website features several pages including vehicle tracking, vehicle statistics, charging station status, charging station statistics, billing, heat maps, journeys lists, charging lists, mobile tracking, and more. Depending on the type of user (station operator, station user or EV tracker) some pages are restricted or hidden. The website is a secure HTML 5 site with live information, interactive maps, graphs and customizable time scales. The supported browsers are Chrome, IE 12+, Firefox and Safari, allowing access from computers, tablets and smartphones.

A. Vehicle Tracking Features

The tracking page (see Fig. 3) displays the vehicles' movement on a map with drive distance, speed and battery usage displayed in a graph. The user can select an individual vehicle or all vehicles in a fleet and the time period to display. The graph is interactive, allowing the user to drag and zoom in on the time scale and can show charging and journey events, as well as the status of air conditioning, headlights and heater in a vehicle.

B. Vehicle Tracking Implementation

The vehicle tracking page uses PHP scripts to supply the information to JavaScript code on the page. The page uses several free-to-use libraries including JQuery for communication with the server, Google Maps for the map and Dygraph for the interactive graph. The Dygraph library is open source and was modified for use in the website.

To display the GPS data, the map has the ability to show individual interactive points that can be clicked on for additional information or an image that is generated by a PHP script on the server. The number of interactive points is limited to 150, as too many points can cause instability in the browser. However, the image overlaid over the map can contain any number of points, which allows users to see data over longer time periods. Generating an image at the server is also useful, because the information sent from the server to the user is significantly less. The server caches all images generated and generates differently scaled images for different map zoom levels.

For performance and stability reasons, the graph below the map is limited to displaying 2,000 points at a time. To reduce the load on the server, the graph caches data and only requests additional information when necessary. When a user pans the graph to the left or right, only the missing information is requested. The granularity of the data is also important and the server is designed to send sub-divided data when the time period selected has more than the 2,000 point maximum. When the user zooms on a section of the graph, the server is asked for sub-divided or raw information for this smaller time period.

C. EV Statistics

The vehicles statistics page (see Fig. 4) displays a summary of all vehicles tracked or an individual vehicle within a user-selected time period. The all-vehicles summary includes fourteen graphs and a vehicle leader board, ranking all vehicles by total distance travelled and stating the time driven, number of total journeys, average journey distance and average journey time.

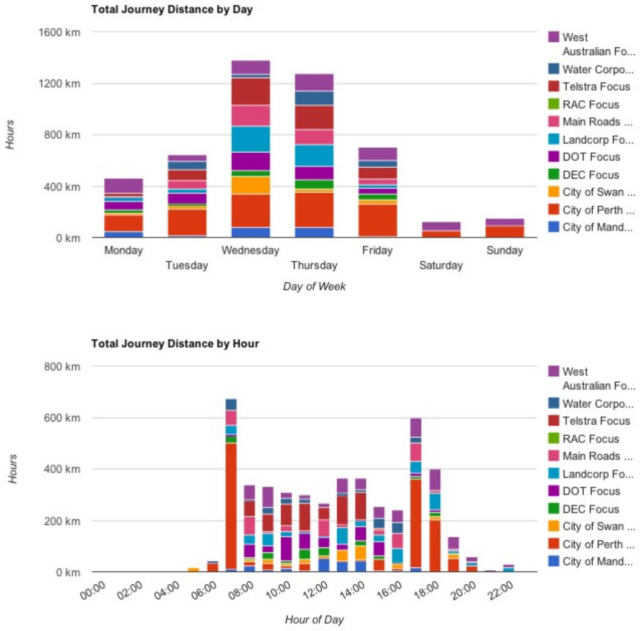


Fig. 4. Tracking page for the REView software

If a single vehicle is selected, a page summarizing its statistics versus the rest of the vehicles (the "community") is shown. This is a 'gamification' feature, which we find useful to keep monthly reports interesting for the users.

D. *Charging Station Statistics*

The "Stations" page displays the statistics of all stations or of an individual station within a selected time period with live status, power in kW, energy in kWh and charging time in hours, minutes and seconds. The user can select a summary of all charging stations or an individual charging station and set a starting and ending time period.

Each of the statistics generated is useful to charging station operators. The table shows:

- Which electricity plan is more useful, displaying the cost of a flat rate of electricity price (e.g. 21.87 c/kWh) and a tiered rate (peak/shoulder/off-peak, e.g. 42.15c, 21.44c and 11.32c per kWh respectively), which charges more during peak times and less during off-peak times.
- Time spent charging the vehicle (drawing more than 1kW) and the time spent plugged in and not charging as a percentage. This shows if a station is more used for charging or if a location is more used as a parking spot.
- Time spent on a transaction (how long the vehicle is plugged in on average).
- Amount of time the station is actually in use versus its total time installed. Showing how often the stations are utilized as an average over all locations.

Select a bill type: ● Vehicle / User ○ Station ○ Summary

Vehicle / User: [redacted]

Time Period Starting: 2014-01-01

The REV Project
M018 35 Stirling Highway
Crawley WA 6009
T +618 6488 3897
F +618 6488 1168
rev@ee.uwa.edu.au
http://therevproject.com

To: [redacted]

Attention:

Tax Invoice
E140141188
Date: 2014-02-01

Total Distance Travelled		Distance Per Charge		kWh per km	
Me	Community	Me	Community	Me	Community
416.9km	323.7km	4.21km	11.27km	0.27 kWh	0.26 kWh

Mobility Cost

DESCRIPTION	EVENTS	kWh	UNIT PRICE	AMOUNT	GST	SUB TOTAL
Home charging (T1 tariff)	0	0.00	0.21	0.00	0.00	0.00
Work charging (T1 tariff)	4	2.23	0.21	0.47	0.05	0.52
Station charging	19	141.51	(avg) 0.25	35.38	3.54	38.92
Other charging (T1 tariff)	71	61.46	0.21	12.91	1.29	14.20
Total Mobility Cost	94	205.20		48.76	4.88	$53.64
				Cost per km		$0.13
				kg CO_2 Saved		70.46

Station Charges

DESCRIPTION	EVENTS	kWh	UNIT PRICE	AMOUNT	GST	SUB TOTAL
[redacted]	19	141.51	(flat) 0.25	35.38	3.54	38.92
TOTAL TO BE PAID	19	141.51		35.38	3.54	$38.92

Fig. 5. An example of the billing page from REView

E. *Billing*

The billing page allows an EV user to view his or her monthly mobility cost. It also lets station operators view utilization and energy usage of their stations. In both cases summaries as well as itemized bills are generated, similar to phone bills. All bills are automatically generated with several informative graphs, including distance travelled, distance per charge and kWh per km of the individual versus the community. Also, a time-of-use energy graph is generated (see Fig. 5).

F. *Heat Maps*

Heat maps are automatically generated and can show areas where vehicles drive, park and charge within certain time periods. These are generated by Python batch scripts as a part of the data processing using the heat maps library written by Jjguy [18].

G. *Mobile Applications*

REView has two mobile phone applications for EV drivers and station users. The first allows users to view their vehicle status on their mobile phone, showing location, status and battery level. The second allows station uses to see if their vehicle is still drawing power or if their EV is fully charged. It also allows users to check remotely if a station is occupied or free, allowing EV drivers to plan their trip ahead. These applications helped ease 'range anxiety' where drivers fear their vehicle will not have enough energy left in the battery to make it to a destination.

Designing mobile web pages instead of apps makes sure they can be used for every smartphone or tablet model. The pages were developed as lightweight web pages using HTML 5 and JavaScript, which communicate periodically with the server for data updates. Each of the charging stations are listed in a page, with their availability indicated by a blue or green icon.

User EVWorks (Rob)
Current kW 3.04 kW
Total kWh 6.07 kWh
Charge Time 37:49:31 hr
Status In use

Fig. 6. Smartphone applications

H. System Administrator Pages

The system administrator can get an overview using journaling pages for all vehicle journeys and charges, as well as specific web pages for support, settings and debugging functions.

VIII. RESULTS

In this section, we will discuss results from the WA Electric Vehicle Trial, represented in REView graphs.

A. Overall Energy Usage

Fig. 7 shows the energy consumed charging EVs by hour of day and location. This information can be used for analyzing EV grid impacts and the usage of renewable energy. The locations are defined as followed:

- Home: A residential area
- Business: A commercial or industrial area
- Station: An EV charging station
- Unknown: An undefined area

The peak of the energy supplied for charging vehicles (averaged over all locations) is during the morning hours around 9–10am. This means, EVs are commuting from home to work and use a charging facility at work (most likely free of charge). It is worth noting that the majority of energy supplied is during sunshine hours especially for station charging and business charging. For unknown and home charging, there is a much smaller peak at around 6pm, for vehicles that are returning home and charging there. This also suggest that the majority of unknown locations are unlabeled home locations.

From this information and solar information gathered (see Fig. 10) we can show that typical charging scenarios can be offset almost ideally by solar technology. Most of the charging occurs during the day, which differs fundamentally from the scenario propagated by some energy suppliers, which shows all EVs charging around 6pm when they return to home.

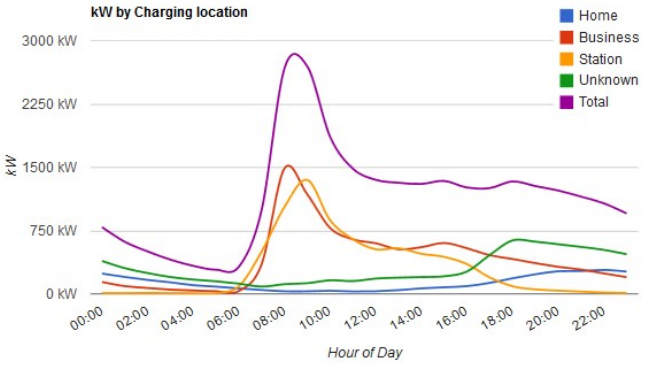


Fig. 7. kW drawn by hour of day for EV charging at various locations

B. EVSE Station Usage

The statistics in this subsection are taken from REView's "Stations" page showing the summary of all charging stations as a part of the WA Charging Station Network, from the beginning in 2011 until May 2014.

In Fig. 8 and Fig. 9 we discuss the difference between charging and maintaining charge. It is common that an electric vehicle charger will draw a large amount of power until the battery pack is full, at which point the charger will continue to draw power at a significantly lower rate. When drawing power at the lower rate the EV can be doing several things including maintaining the charge of the battery pack, pre-conditioning the interior of the vehicle with heating or cooling or maintaining the temperature of the battery pack to improve driving efficiency. To distinguish between charging and maintaining charge, we define a vehicle to be charging if it is drawing more than 1kW of power; otherwise we define it as "maintaining".

From Fig. 8 it is clear that throughout the day the majority of energy consumed from the station is done during a charging cycle. The energy for charging varies heavily depending on the time of day with the majority of energy being used throughout the day, reducing steadily into the evening and bottoming out around midnight. However, the maintaining charge energy consumption is similar in every hour throughout the day and night. This is because the electric vehicles are sometimes parked at the charging station overnight, and possibly over days when the EV is not being used. The maintaining charge consumption remains steady throughout the time the vehicle is idle.

In Fig. 9 we show the amount of time spent for charging and maintaining charge. From the discrepancy between the time required for charging and the time actual spend plugged-in at the charging station, it can be seen that the charging stations in many cases are being misused as free parking locations for EVs.

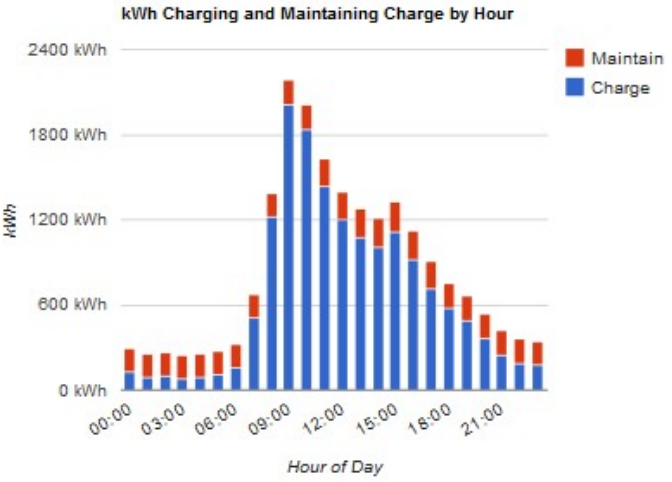


Fig. 8. kW drawn by hour of day stacked with power drawn for charging versus power drawn for maintaining charge

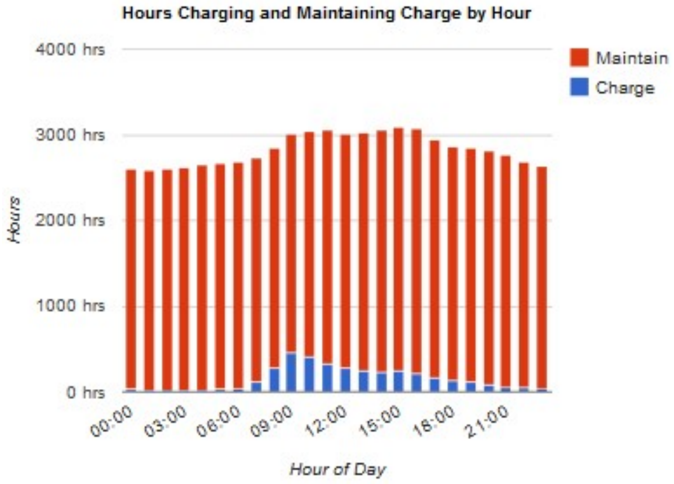


Fig. 9. The amount of time spent at a charging station with stacked charging time and maintaining charge time.

TABLE II. CHARGING STATION FIGURES 1/2011–5/2014 (41 MONTHS)

Total kWh	19635.721 kWh
Estimated Cost (21.87c per	$4294.33
Estimated Cost	$5306.84
Number of Transactions	2992
Plugged in Time	2784 days, 7:50:08
Charging Time	144 days, 11:02:35
Maintaining Charge Time	2639 days, 20:47:33
Avg Transaction Time	22:20:03
Avg Charging Transaction	1:09:31 (5.19%)
Avg Maintaining Time	21:10:31 (94.81%)
Percentage Time in Use	4.41%
Power Used in Peak	8404.96 kWh (42.8%)
Power Used in Shoulder	8227.58 kWh (41.9%)
Power Used in Off-peak	3003.18 kWh (15.29%)

TABLE II. shows the summary of the charging station usage. From the information collected and automatically analyzed, we can draw several conclusions. The flat-rate plan of buying electricity is cheaper than the peak-shoulder-off peak plan. Only 5% of the time spent at a station is used actually charging, while for the remaining 95% of the time, the vehicle sits idle and blocks a charging station. This could allow for vehicle to grid technologies, however, as shown in [19], V2G applications are not cost effective with current battery technology, as the additional wear and tear from extra charge cycles by far outweighs the marginal energy cost. The stations themselves were only in use 4.4% of the time logged, leaving a large proportion of the outlets idle.

C. Solar Technologies

In the graph in Fig. 10 we show the average power output of the 20kW peak solar system at The University of Western Australia per day. The solar system begins generating energy at 6am in the morning and shuts down at 6pm, with peak energy output at 12 noon. The solar system generates approximately 80kWh per day of operation. So, this solar system is generating around 30MWh per year. In comparison, the 23 EV charging stations are using only 5.7MWh per year on average (see TABLE II.). This shows that one large solar PV installation can effectively power a number of EV charging stations.

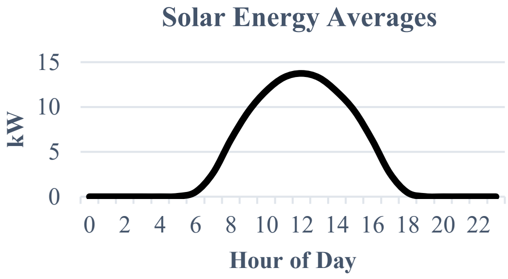


Fig. 10. Average power output of the 20kW solar system at UWA

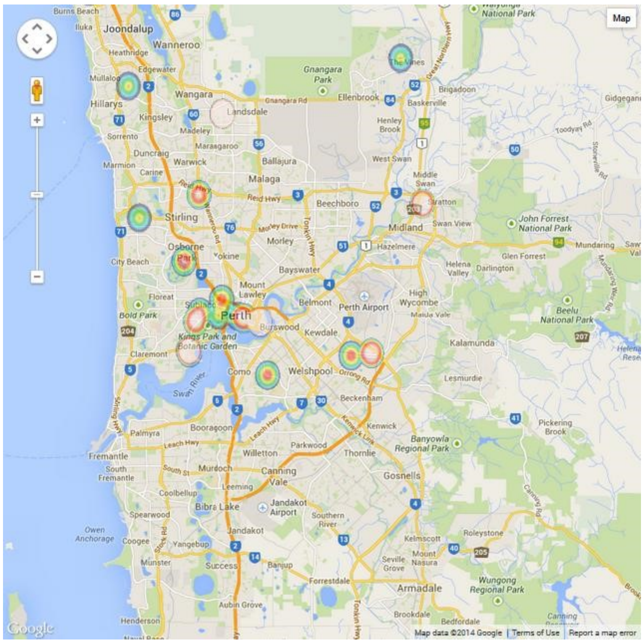


Fig. 11. Heat map of possible charging locations that are utilised during the day (7am to 6pm)

D. *Heatmaps for EV Parking*

We generated a heat map of the charging locations for tracked EVs from 2010 to July 2014. By looking at the charge events that took place during the day between 7am and 6pm, we can identify possible public locations in the Perth Metro area. The heat map shows several heavily utilized areas, including residential and business locations. One hot spot in Landsdale WA is the location of an EV conversion company that services most of the tracked EVs. From the heat map, we can determine that this is a place where a charging station would be highly frequented. The heat map also shows hot spots around most existing stations such as at The University of Western Australia.

IX. CONCLUSIONS

We have presented REView, an integrated web-based tool for monitoring fleets of EVs and managing a network of charging stations. The system comprises live data information portals for customers as well as for fleet operators and charging network operators. It provides statistical information on time and location of charge events and includes a time-of-use billing system.

The REView system interfaces with charging stations, vehicle-based data loggers and solar systems. This requires configuration and testing for each of the different devices in parallel with server and database development. The software was written to use a PostgreSQL database, with software designed in Unix shell scripts, python, PHP, JavaScript, HTML and CSS for server-based and client-based processing and data display.

Each of the different levels of this project (server, data processing, and interface) was developed in tandem to ensure integration. The software was designed in a modular way with separate scripts for individual features, making unit testing easier, reducing integration problems and isolating failures. All of the programming languages used in the system are interpreted, which means that design changes could be made very quickly.

From the data collected and analyzed, we can deduct that solar technology is an effective way for offsetting energy required for charging EVs at public charging stations and place-of-work. For home charging, energy is mostly required outside of solar generation hours and would need to be provided by a domestic energy storage system. A 20kW solar system was more than enough to offset the energy used by EV charging at 23 public charging stations.

ACKNOWLEDGEMENTS

The author would like to thank all partners of the WA Electric Vehicle Trial, as well as the ARC as sponsoring body. We would like to thank all donors and sponsors of the REV Project, especially Galaxy Resources, the WA Department of Transport, and UWA. For the REView project, we would like to especially thank Telstra Australia, who provided us with M2M SIM cards for vehicles and charging stations.

REFERENCES

[1] Mader, T., Bräunl, T., *Western Australian Electric Vehicle Trial – Final Report*, WA EV Trial Consortium, June 2013, pp. (56).

[2] Electric cars dominate at Frankfurt auto show. 2013; Available from: http://phys.org/news/2013-09-electric-cars-dominate-frankfurt-auto.html.

[3] International Energy Agency OECD/IEA, *Global EV Outlook 2016, Beyond one million electric cars*. 2016, pp. (49).

[4] Rodriguez-Serrano, A., Torralba, A., Rodriguez-Valencia, E., *A communication system from EV to EV Service Provider based on OCPP over a wireless network*, Industrial Electronics Society, IECON 2013, 39th Annual Conference of the IEEE, 2013.

[5] AECOM, *Economic Viability of Electric Vehicles* report, 2009.

[6] Kinghorn, R., Kua, D., *Forecast Uptake and Economic Evaluation of Electric Vehicles in Victoria*, May 2011, AECOM.

[7] Roberts, N., media release: *ABMARC releases key findings from their electric & hybrid vehicles report*, 2012.

[8] ESAA, Energy Supply Association of Australia, *Sparking an Electric Vehicle Debate in Australia*, report, Nov. 2013, pp. (54).

[9] Department of Industry Innovation and Science, *Australian Energy Update 2016*, October 2016.

[10] Anair, D., Mahmassani, A., *State of charge: Electric vehicles' global warming emissions and fuel-cost savings across the United States*, Union of Concerned Scientists Report. www. ucsusa. org/assets/documents/clean_vehicles/electric-carglobal-warming-emissions-report. pdf, 2012.

[11] van Namen, K., Tieu A., WA Department of Transport, *Green House Gas Emissions from Households in Western Australia*, project 3006127, 2011.

[12] Green Vehicle Guide. 2014; Available from: http://www.greenvehicleguide.gov.au/GVGPublicUI/SearchResults.aspx.

[13] National Transport Commission Australia, *Carbon Dioxide Emissions from New Australian Vehicles 2013*, May 2014.

[14] EZY2C, *Online GPS Tracking*, 2014; Available from: http://ezy2c.com.au/?gclid=CM-Nl8Wbn MACFZNvvAodSSwAaQ.

[15] Fleetmatics. *Stop losing time and money*. 2014; Available from: http://go.fleetmatics.com.au/au/stop-losing-time-and-money-v2.php.

[16] ReadyTrack, *Fleet, Vehiclke & Personal GPS Tracking Systems in Australia*, 2017; Available from: www.readytrack. com.au

[17] Hill, G., Blythe, P., Suresh, V., *Tracking and managing real world electric vehicle power usage and supply*, Data Fusion & Target Tracking Conference (DF&TT 2012): Algorithms & Applications, 9th IET. 2012.

[18] Jjguy. *Heatmap - Python module to create heatmaps*. 2009; Available from: http://jjguy.com/heatmap/.

[19] Mullan, J., Harries, D., Braunl, T., Whitely, S., *The technical, economic and commercial viability of the vehicle-to-grid concept*, Journal of Energy Policy, vol. 40, issue 6, June 2012, pp. (13)

[20] V. Magana, M. Munoz-Organero, *GAFU: Using a Gamification Tool to Save Fuel*, IEEE Intelligent Transportation Systems Magazine, vol. 7, no. 2, 2015, pp. 58–70

[21] Speidel, S., Bräunl, T., *Driving and charging patterns of electric vehicles for energy usage*, Renewable and Sustainable Energy Reviews, vol. 40, Aug. 2014, pp. 97-110 (14)

[22] Jabeen, F., Olaru, D., Smith, B., Bräunl, T., Speidel, S., *Electric vehicle battery charging behaviour: Findings from a driver survey*, Australasian Transport Research Forum ATRF, 2013, Brisbane, Australia, 2.-4. Oct. 2013, pp. (15)

[23] Speidel, S., Jabeen, F., Olaru, D., Harries, D., Bräunl, T., *Analysis of Western Australian Electric Vehicle and Charging Station Trials*, 35th Australian Transport Research Forum (ATRF), Perth, Sep. 2012, pp. (12)

[24] Jabeen, F., Olaru, D., Smith, B., Bräunl, T., Speidel, S., *Acceptability of Electric Vehicles: Findings from a Driver Survey*, 35th Australian Transport Research Forum (ATRF), Perth, Sep. 2012, pp. (14)

A Comparative Study of AC and DC Electric Vehicle Charging Station Usage

Kai Li Lim, Stuart Speidel, Thomas Bräunl

Abstract — **Fast-DC charging stations can charge an Electric Vehicle (EV) several times faster than Level-2 AC charging stations. Using a network of DC charging stations, it becomes possible to use EVs for long distance, cross-country driving with only short recharging stops. This paper examines and compares typical customer usage patterns at DC fast-charging stations (50kW) versus Level-2 AC stations (7kW). It includes data collected from the University of Western Australia's AC and DC charging network in the Perth metropolitan area, as well as from stations along the highway connecting Perth to Augusta in the rural South West of Western Australia (over 300 km apart). A cost model is also drawn up to calculate the operating cost and break-even requirement across several different styles of charging stations. User behavior and adoption of certain charging infrastructure is crucial for the take up of electric vehicles in general. EV charging standards and infrastructure availability have, therefore, a fundamental influence on the electrification of transport.**

Index Terms—**fast-charging stations, electric vehicles, DC charging, AC charging, user behavior, comparison**

1. INTRODUCTION

ELECTRIC VEHICLES (EVs) are an environmentally friendly alternative to traditional internal combustion engine vehicles (ICE), which are a major contributor of carbon emissions [1]. EVs are emission free if charged from renewable energy sources and they improve urban air quality as well as fuel security [2]. Additionally, they are becoming more and more common on the roads today, with an increase on the roads worldwide from 100,000 vehicles in 2012 to over 1 million in 2016 [3]. This paper discusses the data collected from three different sources—the Western Australian Electric Vehicle Trial [4], The University of Western Australia's fast-charging station [5] and the RAC-funded Electric Highway in Western Australia [6]. Comparing these trials allows the assessment of different charging infrastructure types, different locations and different usage patterns between paying and non-paying customers (e.g. free stations). The current state of EV charging technology, specifically international standards and their adoption in different countries, is also examined by using publicly available information [7]. Electric vehicle adoption has a direct link to the availability of fast-charging infrastructure [8] (though not without contention [9]). The infrastructure installation and maintenance of these charging stations is an expensive process, so having greater clarity on usage patterns can assist organizations in their decision making.

This paper's aim is to give an overview of all charging infrastructure developed to date and the overall necessity of an electric vehicle charging station network. The University of Western Australia's Renewable Energy Vehicle Project (REV) installed Western Australia's first EV charging infrastructure in 2010 as a series of 23 Level-2 ("medium fast") AC charging stations (7.7kW), funded through the WA Electric Vehicle Trial in combination with an ARC Linkage grant [4]. REV later installed Australia's first commercial CCS fast-DC charging station (50kW) in 2014.

Although the EV Trial and REV/UWA had proposed an Electric Highway through Western Australia with several partners, it took over two years until RAC WA eventually funded this network. Funds were given to nine rural communities to install a pair of AC and DC charging stations at each location, plus a tenth at the RAC headquarters in West Perth. The rural locations are Mandurah, Harvey, Bunbury, Busselton, Dunsborough, Margaret River, Augusta, Donnybrook and Nannup. While power is provided free of charge at all UWA stations, users of the Electric Highway have to pay $0.50 per kWh. This is twice the amount of the domestic energy rate, which makes these stations unattractive to local EV owners.

The remainder of this paper is organized as follows. Section 2 presents the various types of EV charging infrastructure from a global to local standpoint. Section 3 explores different EV charging methods and the preferred methods of adoption. Section 4 analyses and compares data collected from the UWA AC and DC charging stations, and the local Electric Highway network. In Section 5, a cost model then drawn using this data from the UWA stations. The data analysis is validated in Section 6 using a similar study before a summary and concluding remarks are drawn in Section 7.

2. AC AND DC CHARGING INFRASTRUCTURE

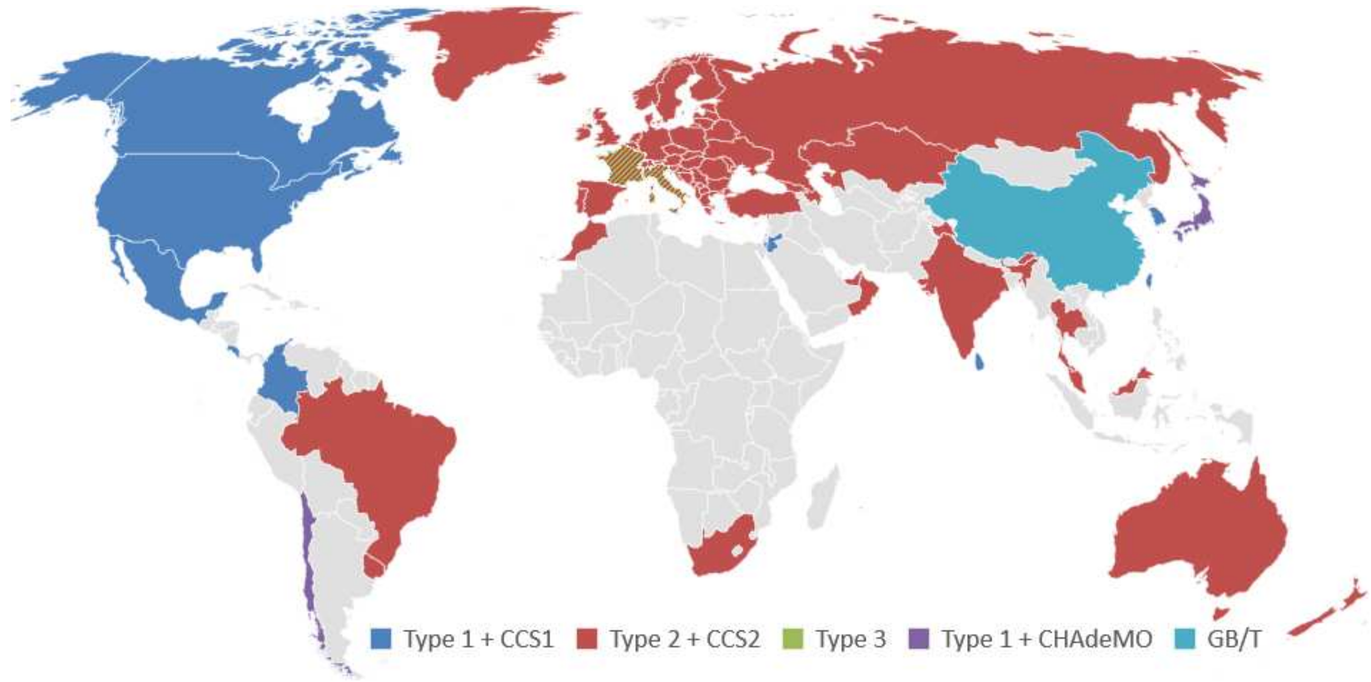


Figure 1. Global EV charging inlet adoption [7]

Countries around the world have adopted different charging standards, and in some cases more than one. The United States and Canada have passed legislation to adopt the IEC 62196 Type-1 standard (single-phase AC), while the European Union has adopted the IEC 62196 Type-2 charging standard (three-phase AC). For DC, these countries use the compatible Combined Charging System (CCS) standard, again as Type-1 (USA, Canada) and Type-2 (Europe), which allows vehicle manufacturers to use a *single combined* vehicle inlet for either AC or DC charging. France and Italy initially adopted Type-3 (Scame) connectors and are currently in transition towards Type-2 connectors.

Japan uses almost exclusively its CHAdeMO standard for DC charging, while China uses its GB/T standard. Some countries, like Australia, have failed to adopt any national standard and then had to suffer the consequences. A mix of Type-1 and Type-2 charging stations were installed in different states in Australia initially when mostly Type-1 vehicles were imported into the country (no EVs were ever produced in Australia). This changed in late 2017, when leading vehicle manufacturers decided to change over to Type-2 for newly imported vehicles, and other manufacturers can be presumed to follow. This leads to presumptions that the whole country should adopt Type-2 stations as a standard which would cause major problems for both charging station operators, as they could not serve all cars (unless they installed Type-2 stations, which have exchangeable power cables), and vehicle owners, who would not be able to charge their cars on CCS stations of the wrong type. Using Type-2 chargers, however, makes sense for Australia, as the country does have a three-phase power grid.

Figure 1 shows each country's predominant AC charging standard in combination with the adopted DC standard. The information used to generate this chart was extracted from the publicly available PlugShare website [7], which claims to be the most accurate source of charging stations worldwide, with approximately 112,000 locations and 170,000+ outlets. Countries that have insufficient or no charging station data are not labeled.

There are several charging standards omitted from this graph, perhaps most importantly the Tesla charging stations, which provide brand-specific chargers in all countries where they distribute their vehicles. In Australia, China and Pakistan, Tesla DC charging stations outnumber all other DC stations, as shown later in Figure 4. When only considering the Type-1, 2 and 3 connectors, Tesla stations outnumber all others in Serbia and Hong Kong.

Charging stations in Western Australia are progressing towards Type-2 chargers. This is inherently visible in recent installations of charging stations, as well as the local charging station networks as follows:

The REV/UWA fast-DC station supports:
- DC CCS Combo Type-2
- DC CHAdeMO

while, the RAC stations provide:
- DC CCS Combo Type-1
- DC CHAdeMO
- AC Type-2 (Mennekes) [10]

This variety of outlets allows the stations to support the different EV standards currently in use. All RAC DC-stations have a Level-2 AC station next to them, allowing vehicles without fast-charging support to charge using an SAE J1772 (Type-1) connector. The power and voltage outputs for charging stations that are commonly found around southwest WA is tabulated as Table 1.

DC Output

Max Output Current	120A
Max Output Power	50kW
Output Voltage Range	50–500VDC

AC Output (three phase)

Max Output Current	63A
Max Output Power	43kW
Output Voltage Range	400VAC

AC Output (single phase)

Max Output Current	32A
Max Output Power	7.2kW
Output Voltage Range	230VAC (+-10%)

Table 1 - Outputs of various charging stations in south-west WA

3. TYPES OF EV CHARGING

There are several different methods of EV charging. When discussing the efficiency of the various methods this paper does not including any transmission losses or power generation. Various power generation methods for electric vehicle charging can be found here [11], [12], with an in-depth comparative study in [13].

Electric vehicles are traditionally charged off AC mains. The AC power needs to be converted into DC power by a rectifier inside the vehicle. Although this makes the charging infrastructure quite simple, each EV must carry an expensive and heavy AC–DC converter element. In many cases, first generation EVs are equipped with only a basic AC charger, useful for Level-1 home charging (max 2.4kW), but not taking advantage of the higher AC currents available at Level-2 charging stations.

The higher the output power of a charger, the heavier and larger the charger must be. Electric vehicles carry this internal charger as a part of their design, to allow charging off a standard electric power point. But at higher currents this method becomes impractical, as larger and heavier AC–DC converters would have to be carried.

DC stations offer a solution for this. Very little electronics is required in the EV itself, as most of the hardware is included in the charging station. First, EV and station negotiate the correct DC voltage level over a communication link. Then the station provides the correct DC level at a much higher current than is feasible with AC charging. The communication protocol used between the charging station and the vehicle is defined by IEC 61851-1 [14].

Signal data lines are part of all charging stations, whether AC or DC, and are fully defined in IEC 62196 and IEC61851. They are also part of safe-guarding stations and EVs against failures and potential hazards. The stations used in the UWA EV trials were equipped with internal over-voltage/over-current protection, over-heating control, and protective earth detection. The stations were also installed on separate circuits with dedicated RCDs, following the conventions of AS/NZS 3000 Wiring Rules.

3.1 Typical Charging Cycle

Electric vehicles go through three or more different states when charging. This can vary from vehicle to vehicle. At a DC charging system, a battery is typically filled up to only 80% capacity, as the charging rate significantly slows down for the remaining 20%, due to the battery's increase in internal resistance [15].

At most AC charging systems, an EV is fully charged to 100%, but even then, it continues to draw a small amount of power to maintain the charge of the battery at the top level. This is to counteract the parasitic draw of various electrical systems in the vehicle, and keep the battery full. Some EVs also condition the battery pack through heating or air conditioning, in order to increase charging efficiency [16], [17] or simply pre-condition the cabin through heating or cooling as a comfort feature for the driver.

Figure 2 shows an EV charged from about 25% to 100% state of charge (SoC) on the DC charging station at UWA. Although this station can provide 50kW of power to the EV, charging begins at 40kW, and as the battery level rises the output power is further reduced. For this reason, all DC charging stations stop charging at 80% SoC. The remaining 20% of charging can take longer than the initial 80% and would preclude other customers from using the charging station.

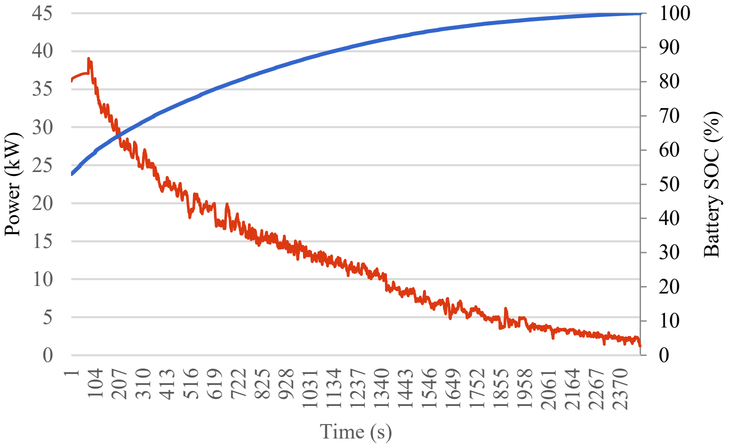


Figure 2. Battery charge rate [kW] in red and State of Charge [%] in blue over time.

3.2 Limitations on Charging Speeds

The following factors limit the effective charging speed (or charging power) of a charging station:

- Temperature of batteries—
  Very high, as well as very low temperatures, require lower charging rates.
- Temperature of tolerable heat dissipation in the power electronics—
  E.g. charging in closed environments, such as a domestic garage has to limit heat dissipation in order to reduce any fire hazard.
- Health of the battery—
  Ageing or unhealthy batteries exhibit a larger variation in individual cell voltages and will therefore require more time for balancing during the charging process.

3.3 Authentication and Billing

Charging station operators may want to control access by some form of user authentication and bill users for their power usage. Authentication can take place in several different ways, including locally at the station (allowing for the station to control authentication without needing an internet connection), or via a server. The charging stations in the REV/UWA trials use RFID cards that were provided to station users. These can be authenticated against an external server. A local whitelist is useful in the event that the station loses its network connection.

Interfaces to manage these stations are also necessary to collate and display the data to users or operators. The Open Charge Point Protocol (OCPP) was developed in an attempt to foster global development, adoption and compliance of communication protocols [18]. This common protocol means that stations from different manufacturers can be controlled by a single OCPP server.

3.4 Driving Efficiency and Battery Size for EV's

There is a significant variation in energy efficiency for EVs [19], ranging between:

BMW i3	129Wh/km,
Mitsubishi I-MiEV	135 Wh/km,
Nissan Leaf	173Wh/km,
Tesla Model S	186Wh/km.

Also, each of these vehicles has a different battery capacity, ranging from the Leaf's 16kWh battery to the Tesla Model S 100kWh battery. For the sake of comparing the different charging stations, two typical scenarios are taken, representing both ends of the spectrum:

- Case 1: 16kWh, 135 Wh/km
- Case 2: 100kWh, 200 Wh/km

3.5 Inductive Charging

Inductive charging allows wireless charging of an EV via an electromagnetic field. There is a coil in the vehicle and one located below the vehicle, usually embedded in a mat. Of the various charging methods, this is the least efficient but the most convenient, as it does not require the driver to plug the vehicle or even to carry a cable. A major issue that manufacturers need to address is that the efficiency is reduced if the coils are not aligned correctly when parked. Only 5% of the surveyed EVs parked within the tolerance level of the coils, so this requires either a movable coil or a self-parking vehicle to reduce this issue [20].

The power transfer efficiency varies depending on the manufacturer, air gap and power rating. In seven different studies between 2011 and 2014 these values were found to be between 83% and 92% [21].

3.6 Level-1 Charging (IEC 62196-3 Mode 2)

Level-1 is limited by the rating of a standard power outlet in the respective country. In Australia, the maximum power to be drawn at Level-1 is 240V at 10A (2.4kW). Electric vehicles are mostly fitted with these chargers internally, as they are comparatively lightweight.

3.7 Level-2 Charging (IEC 61851-3 Mode 3)

Level-2 charging allows the vehicle to draw a higher current up to 32A at 240V (7.7kW for single phase or 23kW for three phase). Like Level-1 charging, this relies on the internal charger of the vehicle.

3.8 DC-Fast Charging (IEC 61851-3 Mode 4)

DC-fast charging ranges from 50–900 VDC and has a range of varying current outputs. Unlike other stations, the charger is not inside the vehicle, but within the station itself. The station's charger is controlled by the vehicle via data lines. The stations in WA support up to 125A (50kW), while Tesla's Supercharger already charges at 120kW [22]. Recent CCS 2.0 stations are supplying up to 350kW per station [23], while future CCS DC chargers will deliver up to 450kW per station [24], [25].

3.9 Alternative Methods

Another potential method of converting AC power into DC for charging the vehicle is through the use of integrated motor drives where the vehicles' motors are used to do the conversion [26].

3.10 Charging Speed Comparison

Table 2 compares the various charging techniques for different battery types and charging levels.

Charging Type	Charge level	Charging time	
		16kWh	100kWh
Level-1	100%	5 hrs	33 hrs
Level-2 (1-phase)	100%	2 hrs	11 hrs
Level-2 (3-phase)	100%	40 mins	3.7 hrs
DC 50kW	80%	15 mins	1.5 hrs
DC 150kW	80%	5 mins	32 mins
DC 450kW	80%	1.7 mins	10.7 mins

Table 2 - Charging style configuration and time for small and large battery packs

3.11 Australian Charging Standard Preference

Figure 3 presents a chart of the number of charging stations installed in Australia. In total 416 stations have been registered at online platform PlugShare.

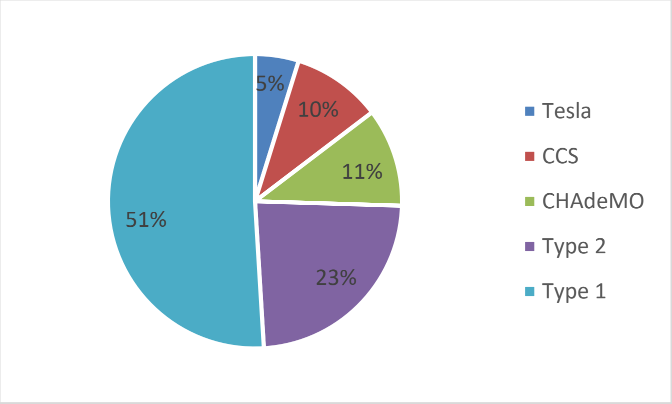


Figure 3. Australian charging inlet adoption

It was observed that there are slightly more installations for CHAdeMO than CCS in Australia, but CCS is expected to take over within two years, as there is a shift to more CCS inlets from major car manufacturers.

BMW as one of the market leaders, has decided to swap over from Type-1 to Type-2 EV inlets for the Australian market and it is expected that will trigger other OEMs to follow suit. Standards Australia has so far failed to recommend any charging standard although the topic has been debated for over ten years. Out of the 416 stations registered, there are:

- 20 Tesla Superchargers,
- 41 CCS,
- 45 CHAdeMO,
- 98 Type-2, and
- 212 Type-1 stations.

3.12 International EV Plug Adoption

The global adoption of DC charging inlets from about 147,911 charging stations worldwide was also analyzed, as illustrated in Figure 4.

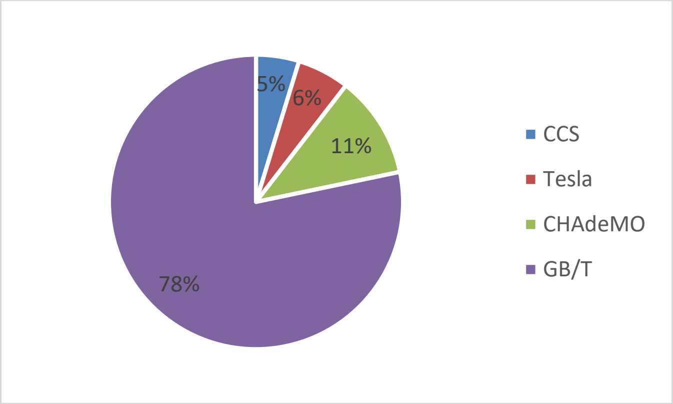


Figure 4. International DC charging inlet adoption

The Chinese GB/T standard has the highest share of all worldwide charging installations, but only exists in China, due to the Chinese government's New Energy Vehicle (NEV) initiatives in 2009, which catalyzed the installations of charging stations around the country [27]. CHAdeMO, originating in Japan, was introduced prior to CCS and has many installations in Japan and North America, leading to its higher market share. Of the charging stations in Figure 4, there are

- 115,776 GB/T DC chargers,
  of which 66,059 are combined AC/DC stations [28]
- 16,639 CHAdeMO stations,
- 8,496 Tesla Superchargers, and
- 7,000 CCS stations [29].

4. ANALYSIS OF CHARGING STATION USAGE

Usage patterns of the UWA/REV charging station network were analyzed, comprising twenty 7kW AC chargers and one 50kW DC-fast charger. Data was obtained during the period of 1 June 2012 to 31 January 2018 for the AC stations, and from 12 November 2014 to 13 October 2017 for the DC station, unless stated otherwise. Short dates are presented in the format dd/mm/yyyy.

4.1 AC Charging and Maintaining Charge

UWA/REV stations are Level-2 stations which typically require a few hours to fully charge a vehicle and therefore many users leave their vehicles charging while they are at work. Many vehicles are hence idly plugged into the charging station even when charging has been completed. Of course, this is mostly because no fees are being collected for charging or for parking at these stations. In this section the charging patterns of the UWA AC stations was analyzed across the data summary tabulated in Table 3. To ensure that only real charging events are logged, events that are less than five minutes long are filtered.

Number of events	4,444
Total energy delivered	29,206kWh
Total plugged in time	672 days

Table 3 - Total statistics for the AC stations across the sample period

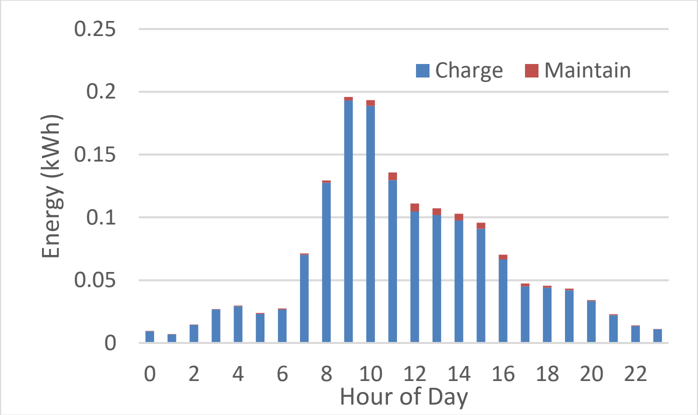


Figure 5. The energy delivered during charging and maintaining charge on average for an AC station at each hour of day.

Figure 5 illustrates the average energy delivery of an AC charging station at each hour of day. Energy delivery increases and peaks at 9 am because it is then when many users arrive at work to charge their vehicle. The energy used to maintain charge increases and peaks at 12 noon, when most of the vehicles have been fully charged. That said, the average energy used to maintain charge on a vehicle averages at only 2.19Wh, which is significantly below the average charging energy of 63.3Wh.

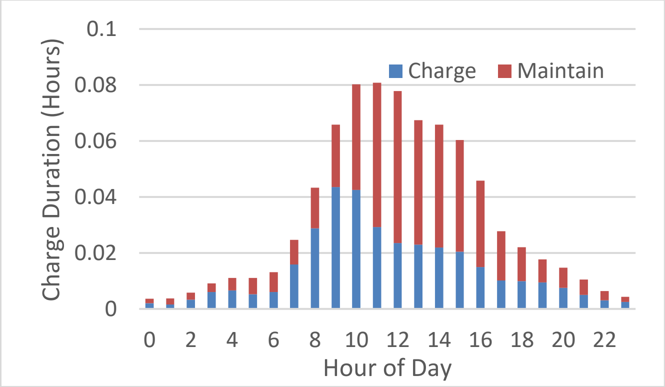


Figure 6. Durations of charging and maintaining AC charge by station time on a vehicle per station at each hour of day.

Figure 6 shows the average time spent for an AC charging station to be in charging or maintaining state over the time of day. As most charging events commence around 9 am to 10 am, more time is spent charging at the station, and as the vehicles get charged, the "charge bar" in the graph eventually transitions into the "maintain bar" for the rest of the vehicle's plug-in time. The charging stations free up in the evenings, before demand increases again in the next morning. In total, the UWA/REV AC stations have spent 312 days charging and 405 days maintaining charge over the data collection time frame, which averages to 0.342 hours charging and 0.431 hours maintaining per day per station. The average charge event at an AC station takes 3.91 hours and uses 6.66kWh of energy.

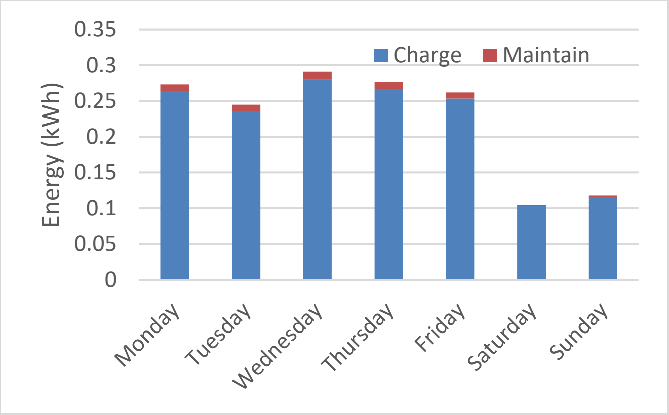


Figure 7. The energy delivered during charging and maintaining charge on average for an AC station for each day of week

By analyzing the charging patterns across a week, Figure 7 indicates that more energy is used during the weekdays for charging, at an average of 0.27kWh per day. Charger usage drops significantly on weekends to less than half at 0.11kWh per day.

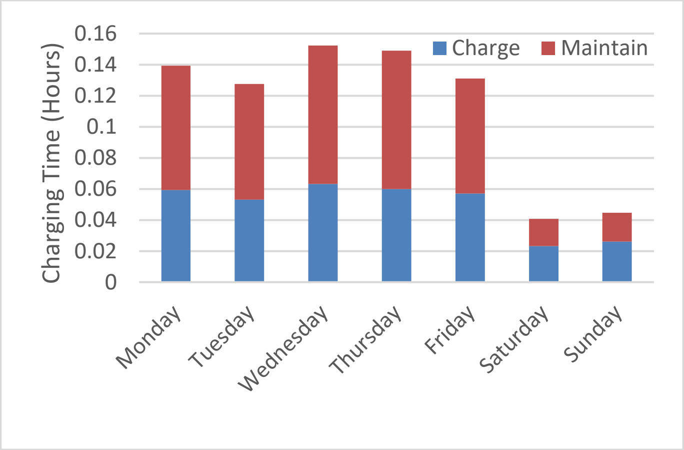


Figure 8. The time taken to charge or maintaining AC charge on a vehicle for each day of week. (CS vs DC)

When comparing charge times across the days of the week, Figure 8 shows that charging duration decreases during the weekends by 53% on average, each station spends 0.14 hours charging and maintaining on weekdays, and 0.043 hours on weekends. This is consistent with the results from Figure 7.

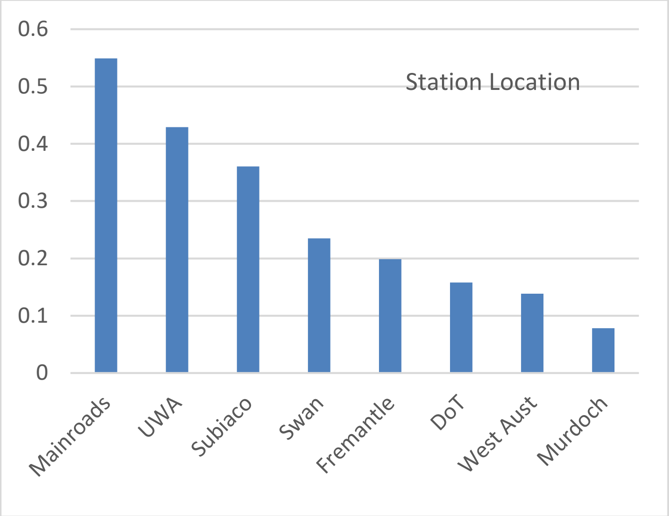


Figure 9. Comparison for the number of chargers per day between each of the AC stations.

A comparison of the average daily number of charge events for each UWA/REV AC charging station is shown in Figure 9. The low number of charges per day is mostly due to slower charging on AC and the fact that cars are not collected when charging is finished, so charging bays are not freed up for new customers. The charger locations near offices and work locations enable their staff to charge on a more consistent basis, but it leaves the stations vacant on weekends. This is evident in the UWA Computer Science and Main Roads stations, where staff charge their vehicles daily on weekdays. The stations in the suburbs of Subiaco and Fremantle are in general parking areas and are more accessible to the public. However, the low EV penetration rate combined with the long charging times contributes to lower charging numbers for these stations. Overall, UWA/REV **AC** stations have on average 0.27 charges per day, ranging from 0.08 to 0.55 charges per day.

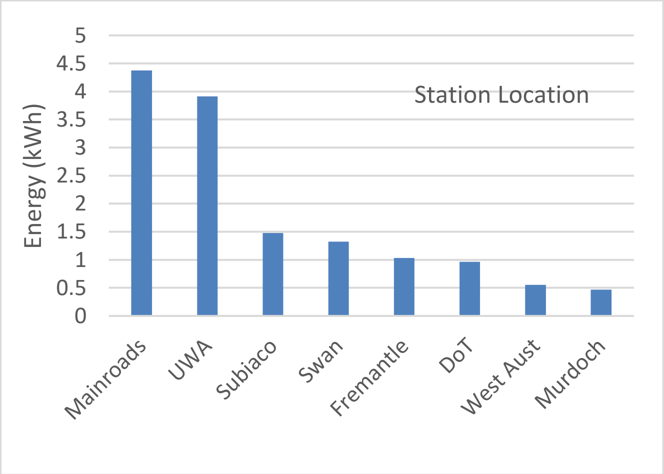


Figure 10. Comparison for the energy delivered at each station per day across each of the AC stations.

By comparing the energy delivery per day for each AC station, Figure 9 shows a similar trend to Figure 10, whereby a higher charge per day will contribute to a higher energy usage for each station. Each station delivers on average 1.76kWh per day, with the Main Roads station delivering the most energy at 4.38kWh per day.

4.2 AC versus DC Station Comparisons (CS vs DC)

A comparison of the UWA/REV fast-DC station against the AC station network at the UWA Computer Science (CS) car park is shown in Figure 11. As expected, the DC station delivers much higher energy amounts in a shorter time than the AC station.

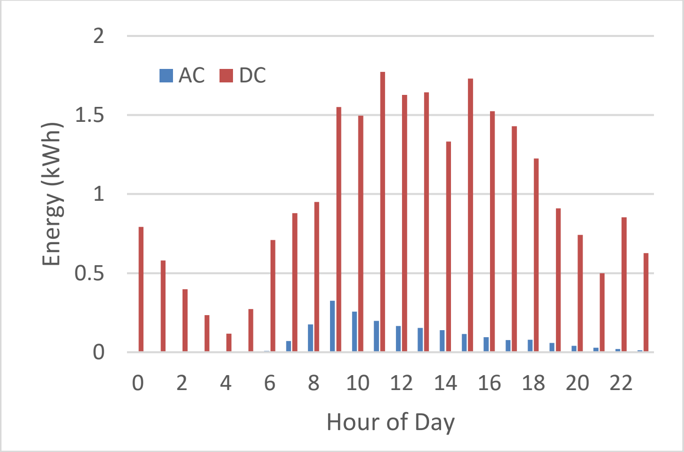


Figure 11. The differences in energy delivered by an AC station versus a DC station at each hour of day. (CS vs DC)

Figure 12 compares the energy usage between the DC station and the AC station across each hour of day based on its charge events. The energy used for the AC station is the sum of its energy delivery during charging and maintaining phases. The DC station uses 7.78 times more energy per hour than the AC station. On average, the AC station delivers 0.09kWh per hour, while the DC station delivers 1.0kWh per hour. Also, while the energy delivery at the AC station peaks at 9 am, charging events at the DC station usually peak later in the morning and continue into the afternoon and evening. The quick charging capability of the DC stations means that users can often charge their vehicle *en route* to their destination.

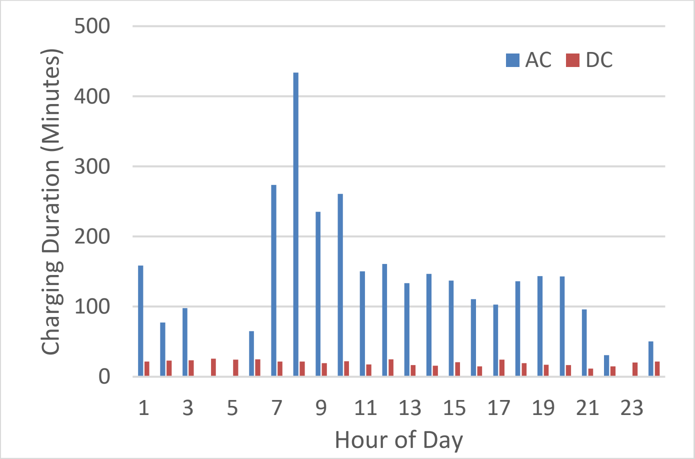


Figure 12. The difference in charging time on an AC station versus a DC station at each hour of day.

Figure 12 compares the charging duration between the UWA DC station and the UWA AC station per hour of day. Charging durations for the AC station is a sum of its charging and maintaining phases. On average, vehicles are tethered to an AC station 6.5 times longer than at a DC station. Even so, there is only a 13.3% difference in the energy delivered between the DC and AC charge events.

It is noted that while charging durations on the AC station are longest for morning arrivals, there is no such noticeable trend for DC charging durations.

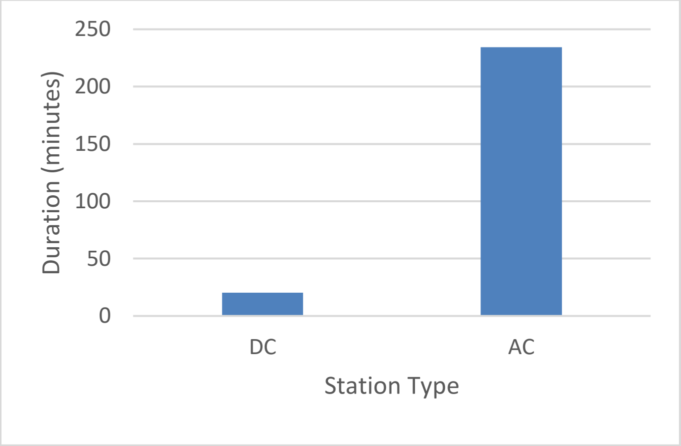


Figure 13. The average charging duration for a DC and AC charge event.

Figure 13 compares the average charging duration for each charge event on the REV/UWA DC and AC stations. The data for AC charging is averaged across all charging events on all AC stations. The average AC charging time across all metropolitan stations is 235 minutes (3h55min) for 6.65kWh, while the average DC charging takes 20.2 minutes for 7.80kWh.

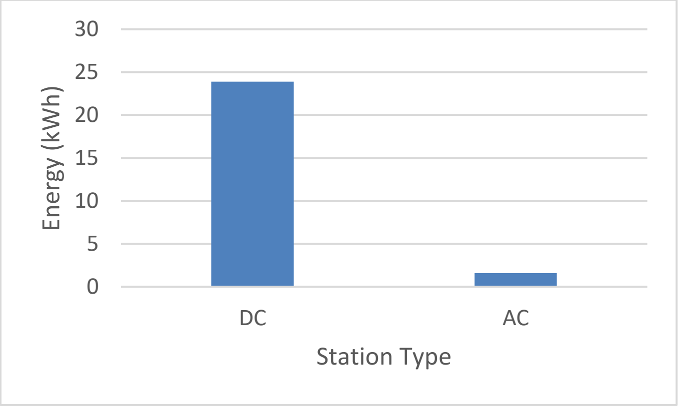


Figure 14. The daily energy delivery for a DC and AC station.

When comparing the daily energy delivery between the AC and DC charging stations, Figure 14 illustrates that the DC station typically delivers 23.9kWh per day, and 1.57kWh per day for an AC station.

4.3 DC Station Comparison

Comparing data from the UWA DC station with the Electric Highway DC stations in the WA South-West, the number of charge events, charging duration and the energy delivered is considered.

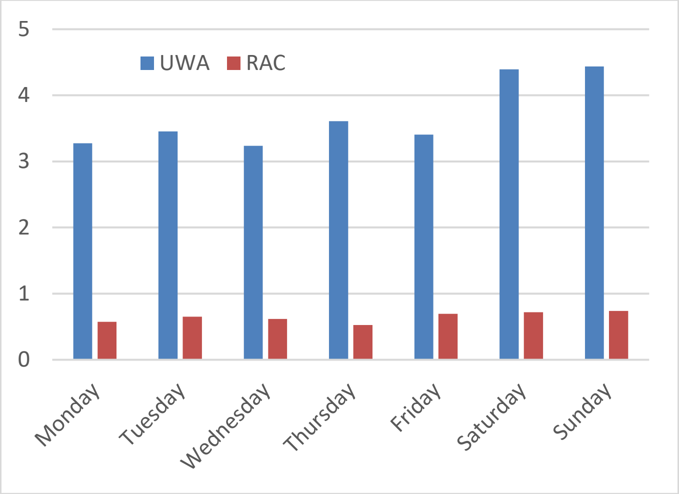


Figure 15. Number of DC charge events per station per day of week between the UWA (12/11/2014 to 13/10/2017) and the Electric Highway (RAC) (02/03/2016 to 20/09/2016).

The number of charges per day of week in Figure 15 compares the average charges at UWA with the RAC stations. The charging data from the RAC stations is compared with the UWA/REV data across 2,370 recorded charging instances beginning from 12 November 2014 to 13 October 2017. The average number of DC charge events is 3.35 per day at UWA, but only 0.65 per day for the average Electric Highway station.

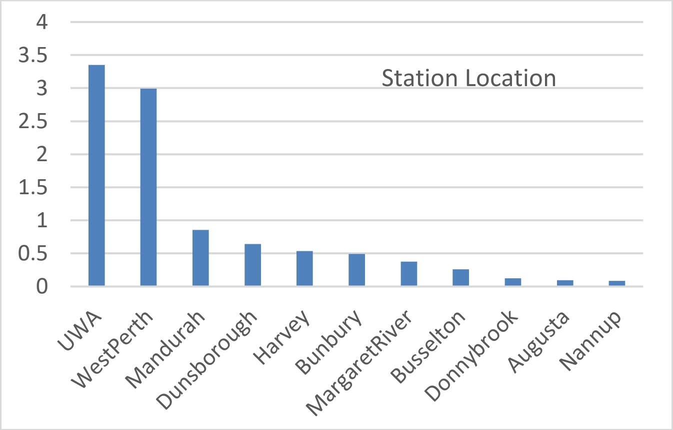


Figure 16. The number of charges per day for each station from the UWA (12/11/2014 to 13/10/2017) and the RAC (02/03/2016 to 20/09/2016).

By comparing the number of charges per day for each station, Figure 16 shows that the stations closer to the Perth CBD are used more often than those in regional areas. The RAC West Perth station has 3.0 charges per day, whereas the UWA station has 3.35 charges per day. The regional stations have significantly fewer than 1.0 charge per day, with Mandurah at 0.86 charges per day, and the lowest being Nannup at 0.087 charge events per day. This puts the average number of charge events of an Electric Highway station to 0.65 charges per day.

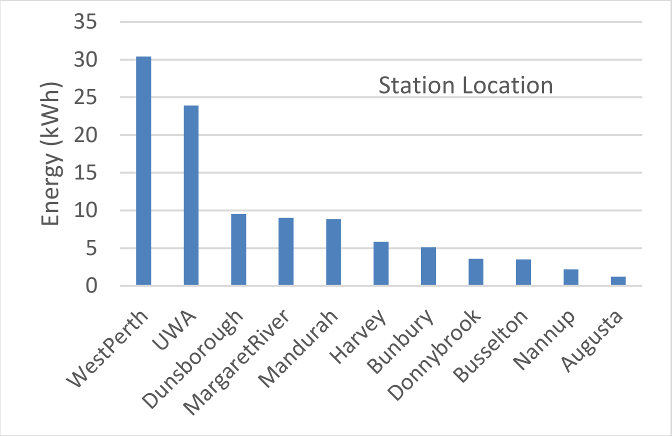


Figure 17. The amount of energy in kWh delivered per day for each DC station from the UWA (12/11/2014 to 13/10/2017) and the RAC (02/03/2016 to 20/09/2016).

Energy delivery across all stations per day is in line with their number of charge events in Figure 16, whereby stations in the city deliver more energy per day. However, despite their lower charging frequency, regional stations deliver more energy per charge as illustrated in Figure 17. The West Perth station delivers the most energy at 30.4kWh per day, followed by the UWA station at 23.9kWh. The Augusta station delivers the least amount of energy at 1.2kWh per day. The average energy delivered by the Electric Highway stations comes to 7.92kWh per day.

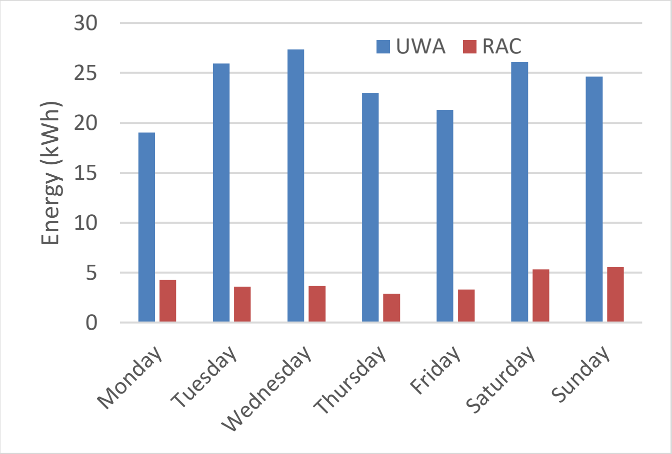


Figure 18. The energy delivered per station per day of week between the UWA (12/11/2014 to 13/10/2017) and the Electric Highway (RAC) (02/03/2016 to 20/09/2016) DC stations.

Figure 18 compares the energy usage between the UWA station and the average Electric Highway station across each day of the week. The Highway stations are more popular during weekends, as more traffic commutes to regional destinations. On average the Highway stations consume 5.55kWh on a Sunday as compared to 2.88kWh on a Thursday. The UWA charging station delivers the most energy on Wednesday with 27.3kWh, and the least on Monday with 19kWh.

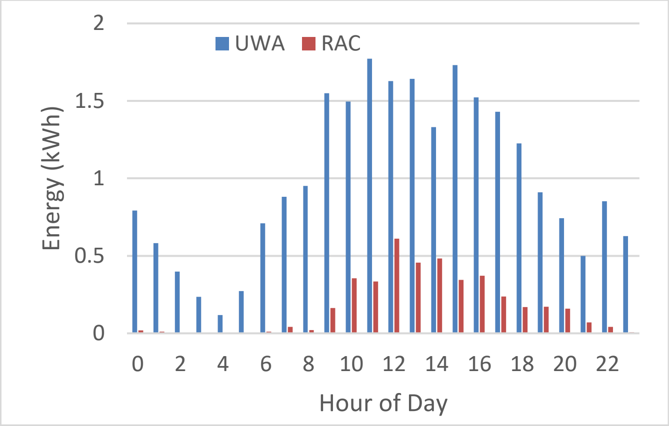


Figure 19. The energy delivered per station per hour of day between the UWA (12/11/2014 to 13/10/2017) and the RAC (02/03/2016 to 20/09/2016) DC stations.

Figure 19 compares the energy consumption per time of day between the UWA station and the average of the RAC charging stations. This data was averaged through all the historical charges on the UWA station, which was then classified to its instantaneous energy consumption at each hourly duration per day. This data is then compared with the data that was obtained from the RAC stations. On average, the UWA station delivers 23.9kWh per day, while the average Highway station delivers 4.08kWh per day.

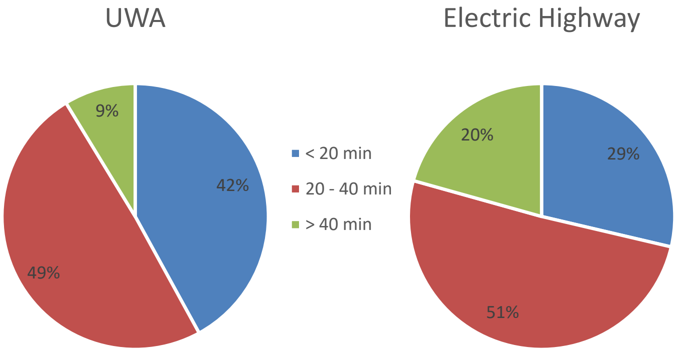


Figure 20. The average charging durations on the UWA (12/11/2014 to 13/10/2017) and the Electric Highway (02/03/2016 to 20/09/2016) DC stations.

Charging durations at the UWA stations, as shown in Figure 20, are predominantly under 40 minutes, which makes up 89% of all charges. The average charging time for the UWA DC station is 22.45 minutes. Half of the charges at the Electric Highway stations take between 20 to 40 minutes, with 29% taking less than 20 minutes. The average charging time for the Electric Highway DC stations is 30.68 minutes.

Type	Owner	Duration (hh:mm)	Energy (kWh)
DC	UWA	00:21	7.128
	Highway	00:31	12.26
AC	UWA (7kW)	05:11	9.881
	Highway (7kW)	02:01	4.313
	Highway (43kW)	01:19	16.69

Table 4 - Comparison of average charging duration and energy consumption for AC and DC stations (02/03/2016 to 20/09/2016).

Table 4 summarizes the average charging duration and energy consumption per charge on AC or DC charging stations of UWA and RAC. Comparing the DC charge times, users of an RAC DC station charge 10 minutes longer on average and delivered 4.6kWh more energy than they do at the UWA station. This is mostly contributed by the West Perth station, which is more frequented by drivers due to its close proximity to the city center, which implies that drivers can visit the nearby shopping center and cafes while their vehicle is charging. Conversely, charging durations are longer at the UWA/REV AC stations (of which half are installed near workplaces) when compared to the RAC 7kW AC stations, which average to about 1.5 hours longer and 2.83kWh more energy delivered. The 43kW fast-AC chargers average at 1.3 hours charge time, delivering 16.69kWh of energy. The average charging time per vehicle on the UWA DC station is 21 minutes to take, on average, 7.1kWh of energy. For the Highway stations, the average charging time is 31 minutes for 12.26kWh of energy.

4.4 DC Charging Connectors Used

Figure 21 compares the types of connectors used at the UWA DC station. CHAdeMO (88%) is in higher demand than CCS (12%) which is because popular EV models from Mitsubishi and Nissan use CHAdeMO, and Tesla provides a CHAdeMO adapter for their vehicles. This trend is set to change with the introduction of more EVs with CCS connectors in Australia from the 2018 model year onwards.

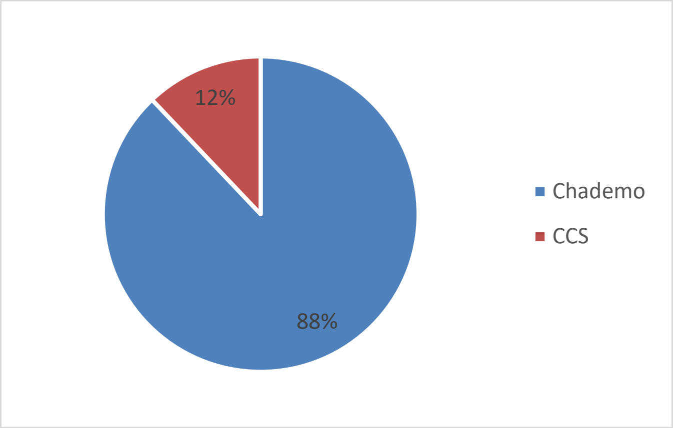


Figure 21. Percentage of connector types used at the UWA DC station (12/11/2014 to 13/10/2017).

5. COST MODELLING

Table 5 introduces a cost model that includes the usage analysis as summarized in Section 4. This is presented as a probabilistic case study for running and maintaining various types of charging stations, namely 7kW AC (AC-7), 50kW DC (DC-50), 150kW DC (DC-150) and 350kW DC (DC-350).

Subject	**Category**	**Unit**	**AC-7**	**DC-50**	**DC-150**	**DC-350**
Running cost	Station cost, C_S	$	3,000	30,000	70,000	127,000
	Installation cost, C_I	$	1,000	6,000	8,000	30,000
	Expected lifespan, t_L	Years	10	10	10	10
	Interest at 5% (average), i	$ / year	109.11	982.03	2,127.73	4,282.74
	Depreciation (constant), D	$ / year	400	3,600	7,800	15,700
	Operating cost / maintenance, C_{Ma}	$ / year	200	400	600	1,000
	Energy supply charge, C_{sup}	$ / day	1.02	1.02	1.02	1.02
	Stations per site, S	Stations	6	6	6	6
	Supply charge per station, $C_{sup/S}$	$ / day	0.17	0.17	0.17	0.17
Cost per day	**Total**	**$ /** day	2.11	13.81	28.99	57.62
	Bay lease per day, C_B	$ / day	10.00	10.00	10.00	10.00
Cost per day with bay	**Total**	**$ /** day	12.11	23.81	38.99	67.62
Energy	Energy tariff, T_E	$ / kWh	0.28327	0.28327	0.28327	0.28327
Sales required to break even, *R*	Without bay [Margin = 50%]	kWh / day	14.90	97.50	204.70	406.80
	Without bay [Margin = 100%]	kWh / day	7.45	48.75	102.35	203.40
	With bay [Margin = 50%]	kWh / day	85.51	168.10	275.30	477.40
	With bay [Margin = 100%]	kWh / day	42.75	84.05	137.65	238.70
Actual use	Actual user count, N	Users / day	0.43	3.35		
	Actual amount of energy per charge, E_C	kWh	9.12	7.13		
	Actual energy delivery at UWA, E_d	kWh / day	3.91	23.90		
	Actual Energy cost, C_E	$ / day	1.11	6.77		
Estimated use for higher EV density (conservative estimate)	User count, N	Users / day	2	10	20	40
	Amount of energy per charge, E_C	kWh	7	15	20	30
	Energy delivery at UWA, E_d	kWh / day	14.00	150.00	400.00	1200.00
	Energy cost, C_E	$ / day	3.97	42.49	113.31	339.93

Table 5 - Cost model of the AC and DC stations according to their power throughout. The 350kW DC station requires a dedicated transformer and substation, which is reflected in its installation cost. Running costs are estimated based on UWA's own 7kW AC and 50kW DC stations costs, and supplier quotes for the 150kW and 350kW DC stations.

The stations' running costs are calculated per day based on the costs associated to their estimated purchasing and installation costs, while assuming a financing option and depreciation of 5% and 8% per annum respectively over its lifespan. Energy tariffs are based on ongoing rates from Synergy, which is the sole residential energy provider in metropolitan WA. Based on observations, new stations are expected to be provisioned for ten years before needing replacements or large-scale maintenance. The total running cost includes estimated ongoing maintenance cost, and the option of parking bay rental. Calculations of the sales required to break even include scenarios where bay rental is needed or otherwise. *Actual* energy and charging time values are based on data collection from the UWA/REV stations. The *estimated use* subject illustrates conservative estimates for utilization of more powerful DC stations under a higher EV adoption rate.

A station running cost C_r is calculated as the sum of its finance interest, depreciation and its operating/maintenance cost per day, adding its energy supply cost and if applicable, its bay lease.

$$C_r = \frac{i + D + C_{Ma}}{365.25} + \frac{C_{sup}}{S}\ [+C_B] \tag{1}$$

Using estimates for i, D, and C_M in Table 5, along C_{sup} provided by Synergy, the running cost for the 7kW AC, 50kW DC, 150kW DC and 350kW DC stations was calculated to be $2.11, $13.81, $28.99 and $57.62 respectively, excluding an estimated bay lease of $10 per day. These figures scale exponentially with the charging station's power output, as more powerful stations are more expensive and require more energy to operate. This is, however, compensated with faster charging durations, allowing a higher charge frequency.

To calculate the required break-even energy sales R for each charging station to break even, scenarios with profit margins M at 50% and 100%, with or without the bay lease of $10/day (B/$\bar{\mathrm{B}}$) were considered. The energy tariff T_E is referenced to Synergy, which at time of writing stands at $0.28327/kWh.

$$R = \frac{C_r}{M \cdot T_E} \tag{2}$$

The calculated sales requirements R to break-even for these four scenarios across the four charging station types is then plotted as illustrated in Figure 22.

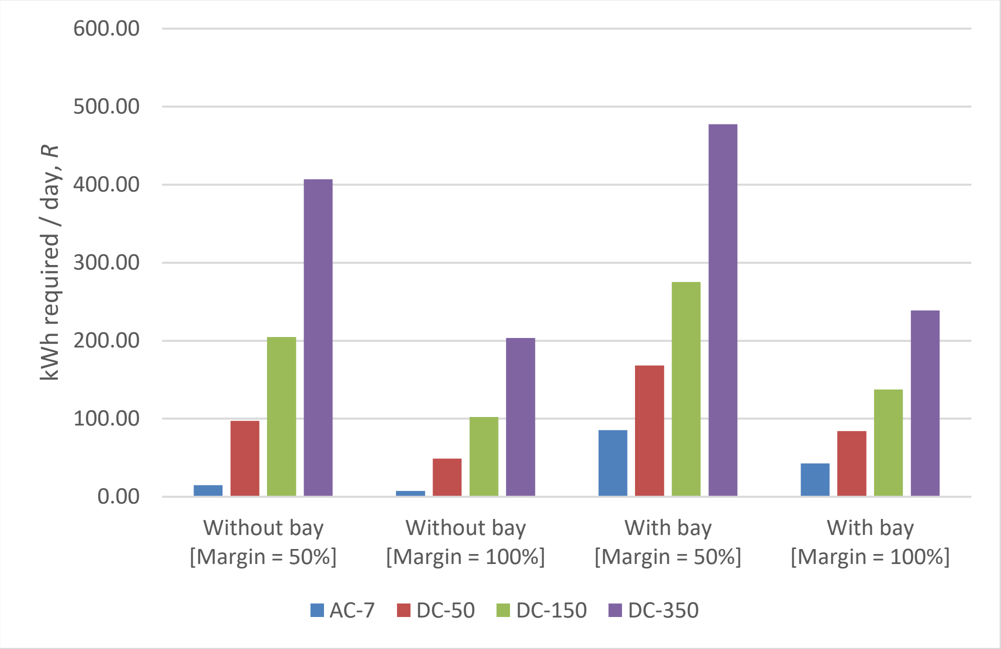


Figure 22. Break-even points for AC and DC stations' energy delivery in kWh required under scenarios representing with or without bay rentals C_B (Bay/No bay), with sales margins set at 50% (M=0.5) and 100% (M=1).

From Figure 22, it is clear that any fee for the charging bay rental C_B increases the required break-even energy sales requirement R, but it has a lower relative effect on the higher-output DC stations, which are expected to sell more energy per day accordingly. For instance, the presence of the bay rental fee C_B across both margins increases the break-even point R by 573% on the 7kW AC station, which means this station will never be profitable in this scenario.

For 50kW, 150kW and 350kW DC stations, break-even point R increases to 172%, 134% and 117%, respectively. This results in less impact for faster stations. Increasing the sales margins from 50% to 100% halves the break-even point R across all stations and C_B scenarios.

The collected data in Sections 4.1 and 4.3 was subsequently utilized to measure the actual usage of the 7kW AC and 50kW DC stations, the energy delivery E_d is defined as the product of the number of users N and the average energy use per charge E_C.

$$E_d = N \cdot E_C \tag{3}$$

The energy cost C_E at that station is thus determined by the energy tariff T_E.

$$C_E = T_E \cdot E_d \tag{4}$$

By drawing a conservative estimate that anticipates a higher EV penetration density, a three to four-fold increase in users per day is expected across the 7kW AC and 50kW DC station, and more daily users for 150kW and 350kW DC stations once they are available.

6. VALIDATION

A similar study was performed in Ireland, finishing in 2016 [30]. This study first investigates the EV charging landscape in Ireland, while drawing comparisons to other European countries. The authors noticed that the numerous EV adoption strategies and incentives undertaken by these countries are contributing to the large growth of EV sales, which introduces a demand for charging stations. The authors then analyzed the usage of 711 charging stations, including 83 DC fast-chargers in Ireland and Northern Ireland through their recorded charge events. Comparisons were performed on aggregated standard and fast-DC charge point datasets, use cases for standard charge points, and use cases for fast-charge points. From these comparisons, the authors then deduced that slow AC chargers have more usage throughout the day, compared to fast chargers that see more usage through the evening and night, which is consistent with the findings presented in this paper. Additionally, the average charge duration for fast chargers is 36 minutes versus three hours for standard chargers, which is also comparable to this paper's findings. To the best of the authors' knowledge this work presents the only other analysis of charging station usages in a geographic location.

7. SUMMARY AND CONCLUSION

While it makes a significant difference, whether charging energy is provided free of charge or for a nominal fee, the location of the stations is also a fundamental factor. While originally proposed as an Electric Highway by UWA, the RAC in cooperation with the local councils decided to place charging stations in the local town centers instead of in proximity to the bypassing highway. The idea was probably that with the low number of EVs at this stage, the local communities should also benefit from this charging infrastructure. However, introducing power charges at about twice the rate of domestic fees made sure that locals will not use these chargers. Why would they use a charging station if they can charge for half the cost at their nearby home (or practically free if they have solar PV)?

As battery technology continues to evolve, EVs with larger batteries are coming onto the market. This means that public Level-1 and Level-2 AC charging infrastructure will become obsolete. The market is expected to shift such that AC charging is being used exclusively for home charging, while all public infrastructure will be DC charging.

The costs of the infrastructure, coupled with the consistently changing technology makes such an investment quite risky, considering the lifecycle and return on investment. Only where massive government incentives or investor capital are available do these projects become feasible. Even then, the infrastructure will only be utilized when the vehicle itself does not have access to home charging. So, if one tries a comparison with the existing petrol station network, only about 10% of all charges are expected to need public infrastructure. Of course, this number highly depends on the local housing environment. The higher the percentage of people who live in houses with garages (as is the case in Western Australia), as opposed to apartments without any EV charging options, the lower the infrastructure requirement will be.

The major factors in EV adoption remain the initial purchase price (which is closely tied to $/kWh battery prices) followed by the availability—or possibly just the perception of availability—of EV charging infrastructure. For modern EVs, range and charging times are almost on par with ICE vehicles, so these points should no longer play a role in purchase decisions.

REFERENCES

[1] Department of Infrastructure and Regional Development, "Vehicle emissions standards for cleaner air." Australian Government, Dec-2016.

[2] ClimateWorks Australia, "The Path Forward for Electric Vehicles in Australia," ClimateWorks Publication, Melbourne, Australia, Apr. 2016.

[3] "Worldwide number of electric vehicles in use from 2012 to 2016 (in 1,000s)*," *Statista*, 2016. [Online]. Available: https://www.statista.com/statistics/270603/worldwide-number-of-hybrid-and-electric-vehicles-since-2009/. [Accessed: 06-Feb-2016].

[4] T. Mader and T. Bräunl, "Western Australian Electric Vehicle Trial," The University of Western Australia, Perth, Australia, 2013.

[5] "Electric Vehicle DC Fast-Charging Station," *The REV Project*, Dec-2017. [Online]. Available: http://therevproject.com/trials/dc-charging-trial.php. [Accessed: 02-Feb-2018].

[6] RAC WA, "RAC Electric Highway." [Online]. Available: http://electrichighway.rac.com.au/. [Accessed: 02-Feb-2018].

[7] PlugShare, "What is PlugShare and why should I use it?" [Online]. Available: http://faq.plugshare.com/article/7-why-should-i-use-plugshare.

[8] F. Gebauer, R. Vilimek, A. Keinath, and C.-C. Carbon, "Changing attitudes towards e-mobility by actively elaborating fast-charging technology," *Technol. Forecast. Soc. Change*, vol. 106, pp. 31–36, 2016.

[9] J. Bailey, A. Miele, and J. Axsen, "Is awareness of public charging associated with consumer interest in plug-in electric vehicles?," *Transp. Res. Part Transp. Environ.*, vol. 36, pp. 1–9, May 2015.

[10] "IEEE Standard Technical Specifications of a DC Quick Charger for Use with Electric Vehicles," *IEEE Std 2030.1.1-2015*. pp. 1–97, 2016.

[11] S. Speidel and T. Bräunl, "Leaving the grid—The effect of combining home energy storage with renewable energy generation," *Renew. Sustain. Energy Rev.*, vol. 60, pp. 1213–1224, 2016.

[12] R. M. Dell, P. T. Moseley, D. A. J. Rand, R. M. Dell, P. T. Moseley, and D. A. J. Rand, “Chapter 6 – Mains Electricity Supply for Charging Vehicle Batteries,” in *Towards Sustainable Road Transport*, 2014, pp. 193–216.

[13] J. Martínez-Lao, F. G. Montoya, M. G. Montoya, and F. Manzano-Agugliaro, “Electric vehicles in Spain: An overview of charging systems,” *Renew. Sustain. Energy Rev.*, vol. 77, pp. 970–983, Sep. 2017.

[14] International Electrotechnical Commission, “IEC 61851-1:2017,” *IEC Webstore*, 07-Feb-2017. [Online]. Available: https://webstore.iec.ch/publication/33644. [Accessed: 02-Feb-2018].

[15] Tritium Pty Ltd, “Veefil--Electric vehicle fast charger instruction manual.” Tritium Pty Ltd, 2015.

[16] Q. Wang, B. Jiang, B. Li, and Y. Yan, “A critical review of thermal management models and solutions of lithium-ion batteries for the development of pure electric vehicles,” *Renewable and Sustainable Energy Reviews*, vol. 64. 2016.

[17] K. Bullis, “Electric Vehicles Out in the Cold,” *MIT Technology Review*, 2013.

[18] Open Charge Alliance, “OCPP 1.6, OCPP, Protocols - Open Charge Alliance.” [Online]. Available: http://www.openchargealliance.org/protocols/ocpp/ocpp-16/. [Accessed: 02-Feb-2018].

[19] “Green Vehicle Guide,” *The Australian Department of Infrastructure and Regional Development*, 2017. [Online]. Available: https://www.greenvehicleguide.gov.au/. [Accessed: 07-Feb-2017].

[20] S. A. Birrell, D. Wilson, C. P. Yang, G. Dhadyalla, and P. Jennings, “How driver behaviour and parking alignment affects inductive charging systems for electric vehicles,” *Transp. Res. Part C Emerg. Technol.*, vol. 58, pp. 721–731, 2015.

[21] K. A. Kalwar, M. Aamir, and S. Mekhilef, “Inductively coupled power transfer (ICPT) for electric vehicle charging – A review,” *Renew. Sustain. Energy Rev.*, vol. 47, pp. 462–475, 2015.

[22] Tesla, “Supercharger,” 2017. [Online]. Available: https://www.tesla.com/en_AU/supercharger.

[23] Charging Interface Initiative e. V., “CCS Specification,” 18-Jan-2018. [Online]. Available: http://www.charinev.org/ccs-at-a-glance/ccs-specification/. [Accessed: 02-Feb-2018].

[24] F. Lambert, “BMW and Porsche join forces to enable 15-min electric car charging at 450 kW charge rate,” *Electrek*, 05-Dec-2017. .

[25] M. Kane, “FastCharge Now Evaluating 450 kW Charging,” *InsideEVs*, 06-Dec-2017. .

[26] J. S. Johansen, “Fast-Charging Electric Vehicles using AC,” Technical University of Denmark, 2013.

[27] Z. Ji and X. Huang, “Plug-in electric vehicle charging infrastructure deployment of China towards 2020: Policies, methodologies, and challenges,” *Renew. Sustain. Energy Rev.*, vol. 90, pp. 710–727, Jul. 2018.

[28] China Electric Vehicle Charging Infrastructure Promotion Alliance, “Zhongguo diandong qiche chongdian jichu sheshi fazhan niandu baogao 2016-2017 ban [China Electric Vehicle Charging Infrastructure Development Annual Report 2016-2017 Edition],” National Energy Administration, Beijing, China, Apr. 2017.

[29] C. Steitz, “Plug wars: the battle for electric car supremacy,” *Reuters*, 24-Jan-2018.

[30] P. Morrissey, P. Weldon, and M. O’Mahony, “Future standard and fast charging infrastructure planning: An analysis of electric vehicle charging behaviour,” *Energy Policy*, vol. 89, pp. 257–270, 2016.

Conclusion

The research was aimed at creating an overall perspective of EV usage in Western Australia. The four major focus areas were EV driving behaviours, charging infrastructure, interconnectivity and renewable energies. The focus areas represent the integration required for EVs to become an alternative method of transportation to ICE vehicles. Below is a summary of the main findings from the trials and associated research, under each of the focus areas:

EV Driving Behaviour

The ICE vehicles converted to EVs for the trial had less than 130 km of drivable range, which is quite limited compared to the newer OEM vehicles released on the market today. From the data collected from the West Australian EV trial, they had more than enough charge to be functional, with 83 percent of charge events occurring when the vehicle still had more than half of its maximum allowable range remaining. Despite having sufficient range before requiring a charge, drivers would almost always plug in, due to range anxiety in operating the vehicles. The vehicles on average were used an hour a day and spent 23 hours idle at various locations.

EVs were driven in the same manner as regular ICE vehicles, with the majority of the driving occurring at the same time in both vehicle types.

Renewable Energy

When compared to ICE vehicles, EVs have the potential for lower environmental impact through reduced carbon emissions and lower maintenance costs. Throughout the life cycle of electric vehicles, carbon emissions are still incurred. These are caused in part by the mining of raw materials, their manufacturing, the delivery to the customer, disposal and any required supporting infrastructure in the form of charging stations/locations. However, even when charged from non-renewable energy sources such as coal or natural gas, EVs cause less emissions than a similar sized ICE vehicle and the power generation emissions are typically in less densely populated areas. To maintain low carbon emissions, renewable energy is the ideal source for charging EVs.

The energy usage of EVs and their impact on the electrical infrastructure is heavily dependent on when and where they were charged. The research from our trials showed that the charging locations used are at the start or end of trip destination. Peak charging times were during mid-morning for public charging stations and during the early evening for home charging. In either case, charging occurs outside of the time of optimal solar energy generation. However, with vehicles parked and charged at the workplace, smart charging controls can communicate with the stations to shift charging to when solar power or wind energy is available. With home charging occurring after hours, there is little opportunity to charge directly from solar energy, but smart charging systems could shift the charging to a time when there is either an abundance of wind energy in the grid or surplus energy from the base load of coal-fired power stations. The use of home energy storage is another viable solution.

Charging infrastructure

Throughout the trial, it became clear that the vehicles often adopted a ‘base charging location’. On average for each vehicle, 59% of their charges occurred in the same location, an additional 23% at a second ‘base charging location’, and only 18% of charging occurred outside of these two locations. We can then surmise that installed charging stations would only have a maximum utilisation of 18% of the active EVs on the road, given that they were not considered a ‘base charging location’.

When EVs initially plugged into charge at a charging station, they draw the maximum amount of energy from the station as possible. When their battery reaches 100%, the energy draw drops back to maintenance, using very little electricity. It should be mentioned that throughout our trial, both parking as well as charging energy was provided free of charge and there were no time limitations in place. When parking at level one or level two stations, the vehicles would spend on average 8% of the time actually charging, and 92% of the total time in maintenance mode, (plugged in, maintaining full charge). On average from plugging in, EVs only needed to recover 20% of their total battery capacity. Charging stations are misused as free parking bays and occupied for exceedingly long times. This makes the economics of getting EV users to pay for energy usage at long term parking locations less profitable than simply getting them to pay for the parking.

With the level one and level two charging stations, the cost of the installation and maintenance of infrastructure, and the underutilisation of the stations makes it impractical to install them for public use in most situations. The research revealed that EV users are discouraged from utilising the stations when the cost of the power is greater than that of their ‘base charging location’. The best use for these stations is when they installed at an EV ‘base charging location’, such as the home or workplace. In this case, the advantages of a charging station over a regular power socket is:

- Enhanced safety and security, where the stations and connectors have additional protection from electrical faults, weather and vandalism
- Monitoring of usage
- Smart charging controls (as a future technology to be further investigated).

The amount of battery storage available in an EV is more than enough to allow the driver to deviate from their average path travelled before returning to a slow charging location. In instances where the vehicle had depleted its battery, the research found that the long charging times of level one or two charging stations were inconvenient for drivers.

The UWA DC Fast charging station allowed trial participants to charge for free, while the RAC Electric Highway stations require EV users to pay for their electricity usage, which as it was higher than the cost of electricity from a slower home charging location, discouraged usage. This made these stations only attractive as a charging location when the vehicle has a very low state of charge or on extended road trips when there is no other charging alternative. The benefit of DC charging stations is, is that they charge an EV about seven (50kW DC) to 50 times (350kW DC) faster than their AC counterparts. Fast DC charging stations are much more expensive and complex to build and install, as well as their necessity for a location that can provide the required grid power. This could be mitigated with energy storage systems, that can directly provide the DC power to the EV. However, energy storage systems are expensive and to charge multiple vehicles their size/cost directly depends on the amount of usage of the station and the range of the vehicles they charge. As once the energy storage system is depleted it would require time to recharge itself from renewable energy sources or the grid.

DC charging infrastructure should be adopted in two different ways. The first, for charging of vehicles that are within their driving range but have depleted their charge, should be installed sporadically throughout major metropolitan areas. The second for vehicles that are on longer trips, such as interstate travel, should be placed along major routes to make long distance EV travel possible.

Charging infrastructure connector standards

Throughout the trials multiple differing standards of connectors for charging infrastructure were installed throughout Western Australia by various different companies. For level 1 and level 2 charging, the SAE J1772 (Type 1) and Mennekes (Type 2) connectors were competing, and in our trials to connect to various outlets, we needed to provide three different cable types (one for standard outlet charging) for the various EVs available. In our charging station roll out, we opted for Mennekes sockets, matching Australia's 3-phase electricity network, but as OEMs started rolling out, many opted for SAE J1772 on their vehicles. However, only a few years later, all new models coming to Australia are now equipped with a Mennekes socket. The research concluded that the Mennekes system should become the standard for Australia's level 1 and level 2 charging, with Combo CCS-Type-2 variant being the choice for DC charging stations.

Interconnectivity

Through the interconnection of EVs, charging infrastructure, and renewable energy data, it becomes possible to show the full life cycle of the energy generation and usage with automated analysis. Charging station providers can authorise, measure and report on the energy usage, the EV drivers can monitor and optimize their driving and charging behaviour and renewable energy installations can be further justified. In addition, interconnectivity of these systems can provide EV drivers with more benefits, such as knowing where a charging location is available, remotely monitoring the status of vehicle charging or booking charging locations in advance to ensure a charging location is available. This data can create real-time awareness for EV drivers, charging stations and renewable energy operators on the benefits of EVs in reducing carbon emissions and cost.

Areas of additional research

To obtain the greatest benefit from reduced carbon emissions, more research needs to be performed into energy storage systems to maximise the amount of renewable energy used by EVs. Incremental renewable energies can then be stored and used to charge EVs when they return to the charging site and could potentially provide a much faster charging speed. How this integration could be achieved and what it means for the life cycle of EVs could be conducted as future research.

Inductive charging can become a valuable addition to EVs, making them simpler to use and removing the need to carry a cable for vehicle charging. The convenience of this technology could potentially be an incentive for more drivers to adopt EVs. Inductive charging could become an alternative to traditional level 1 and level 2 charging infrastructures in the future but requires research into improving the technology and making it possible for a larger rollout in the EV industry. This technology will face the same standardisation and acceptance challenges as the charging infrastructure that was deployed in our trial as a part of this research.

Vehicle automation will be the next revolution for transportation for the world, increasing safety, optimising driving patterns and reducing labour costs. By having vehicles capable of finding their own charging location, only when needed, there is room for reducing electric vehicle infrastructure and improving renewable energy use. There are many potential research areas in vehicle automation, and it is likely that they will be based on EVs.

Summary

In order to maximise the carbon emission reduction for EVs, they need to be charged from renewable energy sources. This will require energy storage systems when vehicles are to be charged outside of sunshine hours.

Few Australians have so far opted to adopt EVs. At the beginning of this research in 2011, EVs were not available on the market, and only enthusiasts who performed their own conversions had access to them. These vehicles were limited by the battery technology at the time, with the EVs converted in the trial having a maximum range of 130km. The research showed that potential EV adopters' largest concerns around EVs were range anxiety, price and technical problems.

In the last few years, modern EVs have been released by major car manufacturers to the market and battery technology has improved, vastly increasing their range.

Modern EVs available today boast ranges of 350 km and a lot more charging infrastructure has been installed around Australia. The rising range and the drivers' usage of the vehicles show that the availability of charging infrastructure is not as strong a limiting factor today. That means that the technical challenges which impacted EV popularity in 2011 has now been largely resolved and they have been proven to be a suitable alternative to ICE vehicles in most circumstances.

Today the largest concern for potential EV adopters is price. The commonality between countries with high EV adoption is government incentives and industry involvement. In this regard, Australia lags behind, and EV adoption will continue to be stifled until incentives are introduced or the vehicle price drops further.