RACE for 2030
RELIABLE
AFFORDABLE
CLEAN
ENERGY

N1 Opportunity Assessment
Electric vehicles and the grid
Final report 2021

Project team

Monash University
Roger Dargaville
Misita Anwar
Katarina Tomka

UNSW
Amelia Thorpe
Declan Kuch
Alannah Milton

RMIT
Kazi Hasan
Brendan McGrath
Lasantha Meegahapola
Sridevi Tirunagari
Madhi Jalili

Curtin University
Peter Newman
Dean Economou
Ben James
Charlie Hargroves
Mike Mouritz
Marie Verschuer

UTS
Scott Dwyer
Kriti Nagrath

CSIRO
Phillip Paevere
Brian Spak

EPRI
Matt Pellow
Sunhil Chhaya

EA Technology
Paul Barnfather

EV Council
Behyad Jafari

Ultima Capital
John Fick

What is RACE for 2030?
The Reliable Affordable Clean Energy for 2030 Cooperative Research Centre (RACE for 2030 CRC) is a 10-year, $350 million Australian research collaboration involving industry, research, government, and other stakeholders. Its mission is to drive innovation for a secure, affordable, clean energy future.
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Glossary

AEMO   Australian Energy Market Operator

CRC   Cooperative Research Centre

DER   Distributed Energy Resource

DERMS   Distributed Energy Resource Management System

DNSP   Distributed Network Service Provider

ESS   Energy Storage System

EV   Electric Vehicle

G2V   Grid to vehicle

ICE   Internal Combustion Engine

IRG   Industry Reference Group

LV   Low Voltage

MV   Medium Voltage

NREL   National Renewable Energy Laboratory

OA   Opportunity Assessment

OEM   Original Equipment Manufacturer

PHEV   Plug-in hybrid vehicle

PV   Photovoltaics

RACE   Reliable Affordable Clean Energy CRC

ToU   Time of Use

V2G   Vehicle to Grid

V2H   Vehicle to home

V2X   Vehicle to "x"- generic term for vehicle to grid, to home, to premises, etc.

VGI   Vehicle Grid Integration

VRP   Voltage stability, Reliability, and Power loss

Executive Summary

Uptake of Electric Vehicles (EVs) will very likely accelerate over the coming years, with upper end projections of share of new sales of all vehicles in 2030 in Australia approaching 80%, implying a fleet share of around 20-25%. This would lead to an additional load on the electricity grid of 20 GWh per day. If this additional load was spread evenly over the day, it represents a modest increase in demand of 3 to 4%. However, if all EVs were to be plugged in during the evening peak, when most people return home, with each drawing 7kW, the instantaneous load could be over 30 GW, virtually doubling peak electricity demand. Clearly this would be very expensive to accommodate. For this reason, ways to ensure EVs are charged in ways that not only avoid significant detrimental impacts on the grid but can in fact improve the performance of the grid are vital.

This report has been compiled with the expertise of multiple experts across a broad range of disciplines relating to EVs, including vehicle and charging infrastructure, distribution and transmission networks, as well as social science areas of human interactions with technology and urban planning and design. The project assembled an industry reference group representing a wide cross section of stakeholders who provided their expert opinions of the key areas of research required to overcome a long list of potential barriers to successful integration of EVs into the grid and compiled a roadmap of research opportunities to address those barriers.

The key areas of targeted research identified are

- data collection to better understand current trends and behaviours,
- business model design (including tariff structures) to incentive beneficial charging patterns,
- better understanding of consumer behaviour in relation to EV changing,
- impacts of EV adoption on mobility and urban design, and
- design of standards and protocols for EV charging equipment and communication devices between EVs, chargers and distribution networks, retailers or other third parties.

This report provides a comprehensive literature review which sets the basis for a detailed barrier analysis. The output of an industry reference group workshop led to the creation of a list of opportunities that were then collated into the Research Roadmap, as shown below. The main body of the report (Introduction and Project Approach and Methodology) contains the essential information that leads to the research roadmap. The literature review provides the links to the state-of-the-art research, and the appendices contain the output from the workshops.

Research Roadmap

Research Priorities (Impact areas)	Focus Areas (Research opportunities)	Timeframes/Milestones		
		Short term (~next 2 years)	**Medium term** (2-5 years)	**Long term** (5 years and beyond)
Data and Technology (Data repository, Network load and forecasting models)	*Charging Implications (1a, 1c)*	Understanding changing transport patterns and related energy dynamics ** (High impact)	**EV trials with whole of network approaches ***(Very high impact)**	Developing coordinated smart charging approaches **(High impact)
		Developing strategies for local governments and EV charging *(Medium impact)		
		Hardware options (e.g., advances on existing techs) **(High impact)		
	EV Uptake (7a-c, 9c)	Data studies on trend analysis and tipping points *(Medium impact)	**Improving network visibility to see EVs and EV chargers ***(Very high impact)**	Developing common load profiles based on uptake data **(High impact)
	EV Data (7c, 8a-c)	Strategies to inform customers perception of EVs and energy storage not just transport **(High impact)	Creating an independent data curator / concierge *(Medium impact)	
		Education, awareness, and customer engagement strategies **(High impact)		
Market and Pricing (Pricing models, Tariff design)	*EV Tariffs (4a, 6b)*	Understanding price sensitive demand of EVs *(Medium impact)	Tariff design and impact on customer behaviour to shift loads **(High impact)	

Est. project budget shading scale:	small e.g. up $100K	medium e.g. $100K-$500K	large, e.g. >$500K

Electric Vehicles and the Grid

Research Priorities (Impact areas)	Focus Areas (Research opportunities)	Timeframes/Milestones		
		Short term (~next 2 years)	Medium term (2-5 years)	Long term (5 years and beyond)
Integrated Opportunities (Interoperability, Smart Charging)	*New EV/Grid Business Models* (4b, 6a, 8b-c)	Investigating new business models for EV charging and storage in Australia (including understanding equity, social acceptance, and role of government.) **(High impact)	Demonstrating specific value streams and value stacking opportunities for bi-directional charging of EVs **(High impact)	
Integrated Opportunities (Interoperability, Smart Charging)	*Urban EV Nexus* (1d, 3c, 9b)	**Exploring regulatory and other constraints associated with the integration of energy, mobility and development** (incl. specific considerations for various types of heavy vehicles and public transport options.) ***(Very high impact)**	Demonstrating how energy grids can interact with transport systems and urban development for mutual benefit **(High impact)	
Customer and Culture behaviour (Customer engagement strategy)	*Charging Patterns* (7a, 8a-c)	Behaviour studies on customer attitudes and drivers **(High impact)	Identifying hooks for messaging and engagement *(Medium impact)	
Regulatory and coordination (Technical Standards)	*EV Standards for charging* (1a-b, 3a-b)	Technical standards for bi-directional charger **(High impact)	Interoperability protocols to streamline information exchange **(High impact)	
Regulatory and coordination (Technical Standards)	*EV Standards for communication* (1c, 3a-c)	**Standards and protocols for communication ***(Very high impact)**		

Est. project budget shading scale:	small e.g. up $100k	medium e.g. $100k-$500k	large, e.g. >$500k

A.Introduction

The RACE for 2030 CRC (RACE CRC) N1 theme 'Electric Vehicles and the Grid' investigates how to maximise net benefits of Electric Vehicles (EVs) to electricity consumers, network businesses and their customers while facilitating decarbonisation of the transport sector. The expected rapid growth in EVs creates opportunities as well as challenges for grid integration, including impacts on peak and minimum demand. There is an urgent need to understand EV uptake trends and pathways and how to manage their impact on the grid to minimise cost impacts and to facilitate the use of this very large aggregate battery capacity to support the energy transition.

Preliminary analysis indicates that even a modest increase in EVs and public fast-charging can, if not coordinated, strain the capacity of electricity substations. Optimised integration could convert this potential adverse impact on the grid into a significant opportunity.

The scope of this opportunity assessment includes the review of key domestic and international EV and grid trials, demonstration pilots, existing market research data and analysis, as well as impact and interaction of EVs with the grid at various levels, as well as social research into customer benefits, user patterns, and market incentives. Critically, the EV opportunity assessment team established and consulted with an industry reference group and included international experts and practitioners to help guide the international scope of the project.

1. Literature Review Summary

In the main report we provide a detailed review of the literature and the state of the art of EV uptake, its integration, and its impact on the grid. A brief summary is presented here. The review is reported in the following four areas:

1. Techno-economic assessment of market and technology trends/practices
2. EV grid impact assessments, policy, regulatory framework, and standardisation
3. Urban design and distributed grid management
4. Social science research for EVs

1.1 Techno-economic assessment of market and technology trends/practices

A review of current market and trends on EV shows that EVs will in future be a widely adopted mainstream technology. However, the timing, speed, and extent of the transition to EVs in Australia are still uncertain. A key reason for this is Australia's uncertain policy landscape. Unlike in similar markets internationally, the federal government's position is that subsidising EV purchases does not represent value for money from an emissions reduction perspective. In addition, there are barriers to commercial and other forms of transportation concerning battery versus capacity, pricing, and fast charging requirements.

1.1.1 EV integration to grid

With regards to EV integration to grid, the review looks at barriers and opportunities associated with the national electricity market and EV energy storage and identifies that barriers and opportunities around the national electricity market include:

Barriers and opportunities around the national electricity market include:

- In the long term, electricity load from EVs could equal existing residential sector electricity consumption

- Convenience charging of EVs coincides with existing electricity peak loads

- Uncertain uptake forecasts: Uncertainty of speed and extent of uptake creates uncertainty around extent and type of grid integration investment and actions required. This is critical as investments and research priorities depend on understanding: How many EVs will there be? Where will they be situated? How will they be used? Uptake projections for Australia range from 0.5 to 5M EVs by 2030 and 5M to 20M EVs by 2050 which represent vastly different futures for mobility and the grid at either end of that spectrum.

- Managed charging could mitigate minimum energy demand challenges, increasing network and renewables utilisation, and provide flexibility for using energy stored in EV batteries via Vehicle to Grid (V2G, where EVs discharge to help balance grid scale supply and demand) and Vehicle to Home (V2H, where EVs discharge to meet household demand) opportunities.

Barriers and opportunities around EV energy storage potentials include:

- EV energy usage could approach and potentially exceed residential consumption under highest uptake scenarios.

- Size of storage capacity available can meet significant levels of demand – exceeding total residential consumption significantly even under moderate uptake scenarios.

- The storage capacity of EVs in V2G mode could provide enough energy to back-up the National Electricity Market (5 million EVs discharging at 7kW equals 35 GW)

1.1.2 Charging infrastructure

Public charging and fast charging become more important in environments with limited off-street parking at homes and workplaces and a higher share of long driving distances along national highways. The Australian Government's Future Fuels Strategy has stated that its highest priority is the rollout of EV-charging infrastructure where it is needed. The review reveals that key barriers with respect to public charging infrastructure include:

- The cost of smart, bidirectional, or grid-interactive Level 2 chargers, which is currently higher than stand-alone, non-networked chargers (see later sections)

- Installation/connection costs and regulatory hurdles for both electrical connection and planning approvals for installation of public infrastructure (Note: this barrier also exists for commercial premises and multi-unit dwellings)

- High-powered fast chargers can be a very large load on a grid and can therefore sometimes require significant grid upgrade costs, even if they are only used in short bursts

- Energy costs – commercial tariffs are structured around very high-capacity connections, but unlike many commercial operations operating on these tariffs, for EV charging the capacity is only used for a small amount of time.

One way around the high energy costs and requirement for grid upgrades for high-capacity chargers in remote areas is to install solar PV (Photovoltaics) and stationary batteries to supplement the grid capacity and provide short but infrequent sessions of high-powered charging.

Public charging infrastructure needs to pay attention to optimising charge point sizing. The core objective is to maximise utilisation while minimising cost. This is a complex problem involving trade-offs between multiple conflicting criteria to meet multiple objectives. Factors that need to be considered span economic, commercial, technical, social, environmental, and regulatory considerations. While optimisation of charge point sizing offers benefits to utility providers, charge points operators, drivers, and car manufacturers, barriers include readiness of planning schemes, constraints associated with site access and grid connection, and installation hurdles.

1.1.3 Tariffs and pricing

Time of Use (ToU) and demand/dynamic pricing policies can play a vital role in encouraging EV uptake by potentially reducing electricity costs for charging whilst also minimising unwanted grid impacts from uncontrolled wide-scale EV charging at grid-unfriendly times. Many electricity retailers in Australia offer ToU and demand tariffs to their residential customers, but the uptake is currently low and variable across the country (somewhere between 0% and 20% of customers depending on location). Despite the potential for ToU pricing to drive better utilisation of the grid and potentially a smoother transition to EVs, there are currently no policies which would substantially increase uptake of ToU or demand pricing in the residential sector.

There are limited examples of the translation of the methods to model and optimise the impacts of different pricing incentives into practical tools used by industry. There is also little evidence that the real-world trials that are testing price-driven incentive programs have so far drawn on the sophisticated models and methods developed for academic research to any large extent. A key opportunity in this space is that, once further data are available from real world trials, the theoretical methods and models can be validated, refined, and put to greater use in optimising EV-grid integration.

1.1.4 Charging technologies

Managed and bidirectional charging can impact negatively on EV battery life in certain circumstances. Although V2G/V2H can potentially provide flexibility for smart EV-grid integration, it may not be attractive to the Original Equipment Manufacturers (OEMs) and EV owners if degradation occurs. Conversely, charging can also be managed in a way that maximises battery life but may reduce flexibility for provision of grid services. Selected key barriers to bidirectional charging include:

- Immature EV orchestration or grid integration technological developments like V2G/V2H. These technologies are still emerging, generally not available off the shelf, and not well standardised across vehicles. In some cases, they are also curtailed in EVs for 3rd party access (or not implemented) so that potential value streams from vehicles remain under the control of the EV manufacturers.

- Grid connection hurdles. Bidirectional installations require extra grid connection assessment as they are a generation source; this increases the complexity and time to get approvals for connection.

- Consumer unfamiliarity with V2G. In general EV owners and fleet operators are currently unaware of V2G or aggregation business models.

- Lack of proven business models, privacy issues around data collection and management, immature technology, and limited product availability, along with costs including hardware, operations, platforms, coordination, and battery degradation costs.

Given the significant cost barriers to different types and scales of V2G/V2H implementations, it is important to quantify potential value streams so these can be weighed against the costs.

1.1.5 Trials

The review also provides a snapshot summary of gaps and opportunities related to the trials, pilots, and demonstrations from Australia and internationally that are looking to progress optimised EV-grid integration. Given the very large expense of running trials and the breadth of existing and past initiatives, RACE for 2030 may be in a good position to:

- engage with current trials with the aim of adding value to downstream research based on the data collected. The results should be made public, given the publicly funded aspects of these programs (i.e., IRENA funding)

- Undertake a study that includes detailed meta-analysis of all international EV trials and available EV datasets to identify gaps that are aligned to specific local industry needs; this could be used to inform future trial designs undertaken through the RACE for 2030 or elsewhere.

1.2 EV grid impact assessments, policy/regulatory framework, and standardisation

This section reviews barriers and opportunities of the large-scale adoption and integration of electric vehicles within power grids, focusing on the integration of EV into power grids, related policy and regulatory frameworks, and standards and grid codes.

1.2.1 Integration of EV in power grids

The large-scale integration of electric vehicles into power grids is analysed under four major areas: 1) Electric vehicle charging on networks, 2) System operation and control, 3) V2G operation, and 4) EV orchestration with distributed energy resources (DERs).

The rapid adoption of EVs, combined with localised clustering, would primarily affect the low voltage distribution networks. High EV uptake, network clustering, battery size, charging behaviour and choice around the time of charging are some of the potential causes of major electrical grid impact. EV charging on the network presents challenges with the violation of network voltage limits stipulated in grid codes, capacity limits of network assets (e.g., transformers), protection malfunction, network congestion and network power quality limits. Ensuring the economic operation of the grid is challenging and increases operating and network augmentation costs.

Opportunities for further research from the network perspectives include:

- Coordinated smart charging and discharging integrated with smart metering to optimise time and power demand, reduce daily electricity costs, and more. More studies are required to develop smart-charging approaches to exploit these benefits.

- Optimisation of EV charging scheduling to reduce the network impact by developing machine learning-based methods to model and predict the EV loads accurately.

- More studies on electricity tariff reforms as these also play a significant role in shifting the charging periods from peak to off-peak periods, which mainly impacts on grid stability.

The operation and control aspects of the power grid are affected by the EV battery characteristics, charging technologies, location and time of charging. There is a clear trend towards longer range vehicles (larger capacity batteries), fast charging times, and clustering of chargers that potentially can result in adverse impacts on system security, stability, reliability, and overloading of distribution apparatus. Uncoordinated and uncontrolled charging of EVs impacts on the power system security and stability performance. Challenges include identifying strategic network locations for fast chargers or charging stations and minimising additional start-

ups and shut-downs (increased cycling) that result in high operating and maintenance cost for power generating stations.

Opportunities for further research from an operational and control perspective include:

- Studies on power system stability and security with high penetration of EVs in the power grid to characterise the impact on power grid stability and mitigate potential stability threats

- Further studies on EV aggregation methods to improve system operation and control

- Developing effective TOU tariff schemes by considering both system stability/control and social behavioural aspects

V2G holds the potential of cheap, flexible, and fast-responding storage with electric vehicle batteries. Unfortunately, vehicle compatibility, V2G infrastructure, possible battery degradation, and consumer awareness are just some of the challenges to a faster development and deployment of this technology. Moreover, V2G could also cause a reduction in power quality (resulting in e.g., voltage compliance; harmonics) due to the power being injected into the grid via a converter. Other barriers identified by the review include a lack of optimal scheduling and controlled charging strategies, premature degradation of batteries and an increase of transformer cyclic/non-cyclic heating (due to abrupt bidirectional power flows).

The review identified barriers around EV orchestration with distributed energy resources. Compared to smart charging of EVs, smart V2G provides additional potential for demand response to further reduce the peak load and increase asset utilisation of the network when responding to variations in renewable electricity production. To realise this potential, it is important to overcome the impact on grid stability and power quality of the intermittent nature of PV energy and uncertainty of EV load, and the volatility and intermittent nature of DERs, (i.e., solar PV) and lack of appropriate forecasting models for distributed DERs. Further research is required to optimally orchestrate EV charging and discharging with the DERs to reduce DER curtailment (under high penetration), peak shaving, and energy cost optimisation to EV customers.

1.2.2 Policy and regulatory frameworks

Regulatory barriers are sometimes more challenging than technology barriers. When developing policies to facilitate EV adoption, factors to take into consideration must include financial support schemes for EV purchases, EV supportive electricity pricing schemes, and encouragement of Distributed Network Service Providers (DNSPs) to take an active role in deploying charging stations across their networks. A review of policy and regulatory framework uncovered barriers in the following areas:

- *EV adoption policies and directives*. Regulatory regimes such as integrated system/energy plans suffer from a lack of long-term planning and goal setting for EV grid integration as well as from an absence of country-specific studies and EV-grid integration forecasts. The also lack encouragement to design new electricity market mechanisms and tariff structures for promoting G2V and V2G and policies to encourage smart charging and EV aggregation.

- *Current policies and regulation of public transport and service fleet electrification*. There are currently no economic incentives to relax tolls on roads, parking, provide access to bus lanes, exemptions in driver's license fees, fiscal compensations and so on for EV owners, and a lack of awareness in transforming vehicle fleets. Research is required to

determine which of these would be appropriate to meet overarching goals of improving mobility and reducing carbon emissions across the vehicle fleet.

- *Government incentives to promote EV adoption in private sectors*. There are no policies on annual tax exemptions for EV owners and lack of purchase subsidies. Again, appropriate use of such policies to maximise benefits (not just increase EV ownership) need to be investigated.

In the regulatory space, the following were identified as opportunities for further research:

- Designing integrated energy plans that consider EV adaptation and factor in future EV uptake by using more reliable EV forecasts.

- Developing fleet-focused incentives and policies to increase electric vehicles in the public transportation sector.

- Developing more grid-friendly tariff structures for EV owners that incentivise renewable energy use and optimal user behaviour in terms of grid use.

1.2.3 Standards and grid codes

The global adoption of EVs will require a unified and consistent worldwide standard for EV grid connection. Some aspects of EVs, such as charging plugs, voltage chargers, contact between the vehicle and the chargers, fast and slow-charging systems, measures for the safe operation of the vehicle, people's protection against electrical shocks, and on-board electrical energy storage for the vehicle need to be standardised for safety and reliability.

The reviews of standards and grid codes found that there is a lack of coordination of the standardisation requirements and rules in different layers of the electrical grid network. This also applies to the end user electrical infrastructure, where standards for electric vehicle charging infrastructure and its grid integration requirements for low and medium voltage connection points (e.g., charging stations; smart charging) are lacking or poorly defined. Standardisation limitations on hardware and software for charging stations present barriers to lowering equipment costs and the use of smart charging. There are also barriers in EV grid connection standards, such as the deployment of infrastructure with embedded intelligence with the standards, regulations, and requirements of the national electricity rules (NERs).

Therefore, there are research opportunities to:

- Review and make recommendations for the coordination of standardisation requirements that would be the most suitable for Australia in different layers of the electrical grid network (including end user electrical infrastructure and defining of standards).

- Identify the suitable standardisation of the hardware and software for charging stations (to achieve lower equipment costs and the use of smart charging) and electric vehicle charging infrastructure and their grid integration (LV/MV) requirements (e.g., charging stations; smart charging).

- Identify suitable EV grid codes that are compatible with all relevant Australian grid codes and standards and wit the national electricity rules (NERs).

- Identify policies and regulation of public transport and service fleet electrification. There is currently a lack of economic incentives in terms of relaxations on toll roads, ferries, parking, access to bus lanes, exemptions in driver's license fees, fiscal compensations etc and lack of awareness in transforming vehicle fleets

- Explore the impact of government incentives to promote EV adoption in private sectors. There is currently an absence of policies on annual tax exemptions for EV owners and lack of purchase subsidies

1.3 Urban design and distributed grid management

The review of urban design and distributed grid management in relation to EVs focuses on how a deeper understanding of the interaction of energy, transport, and urban design can assist in the transition to electric transportation by accounting for the role of renewable-powered microgrids in cities, at the edge of the grid, and in remote locations.

The review has revealed barriers in the following areas:

- Urban design and development: These lack consideration of EV transition rates, land use for transport planning, consumer equity, business models for transit EVs and related urban development. They also currently fail to take into account battery optimisation, electric bus integration and consumer behaviour.

- Business model development for edge-of-grid microgrid control and localised generation and storage balance.

- Remote grid considerations: These need to include the scaling of EV storage, cost of independent microgrids, integration with hydrogen generation technology, and increased dependence on vehicle logistics.

Research opportunities identified by the review include:

- Uncovering the relationship between the components of a new NetZero precinct, including on demand electric shared mobility, micro-mobility (e.g., electric bikes and scooters), electrified public transport, and smart V2G orchestration management systems to take advantage of variability in renewable energy supply and stationery and mobile storage of EVs.

- Exploring the policies, business models, and infrastructure needed to ensure a stable and balanced grid to help speed the transition to renewable energy and electrified transportation

- Examining the potential for green hydrogen powered microgrids, especially for heavy vehicles used in mining and freight (this also applies to remote grids).

- Live data collection and exchange for microgrid performance: Developing predictive modelling to forecast microgrid reliability and costs using live traffic, battery, and electrical load data from Australian microgrid projects, and develop a tool to identify precincts where microgrids are viable.

- Developing business models for microgrid growth by investigating how business models and related incentives can motivate stakeholders (vehicle owners, energy providers, developers and government) to support the growth of microgrids.

Research opportunities also exist in relation to the remote grid. These include developing models for understanding the role of EVs in augmenting stationary storage for remote microgrids; developing tools that allow remote communities, or jurisdictions with remote communities, to calculate the set-up costs, running costs, and reliability of renewable powered microgrids and compare these with fossil fuel equivalents (factoring in EVs as part of the energy storage solution); and developing predictive modelling to forecast microgrid reliability and costs using live traffic, battery, and electrical load data from Australian microgrid projects. The latter can be used to develop a tool to identify precincts where stand-alone microgrids are viable and examine

the potential for green hydrogen powered microgrids, especially for heavy vehicles used in mining and freight.

1.4 Social science research of EVs

The importance of understanding the complex and often non-intuitive interactions of humans with technology cannot be underestimated. Research into the kinds of choices people will make regarding accepting changes to the status quo are as important as the technological, economic, and policy areas. EVs will need to be part of a much wider transformation that includes changes to the built environment and urban governance as well as tax and fiscal settings. It is important that we understand the synergies between industry/government and consumers as well as the way in which business and governments engage with and shape the environment in which EVs operate.

The review of social science research on EVs and their integration with the grid reveals an urgent need to undertake studies to better understand how to maximise the benefits of EV integration for users and the wider community. Information gaps include EV-user demographics and purchasing decisions, their charging behaviour, and the social acceptance of EVs as well as maximising benefits through infrastructure planning and sustainable mobilities. Recommended research opportunities include:

- Undertake sociological studies, particularly in the Australian context, to better understand who is using EVs and the factors influencing use by both early and mainstream adopters

- Combatting subversive uses of public EV charging (e.g. 'hogging' of chargers or intentional use during peak demand times)

- Understand emerging charging norms and how these influence and interact with other aspects of user behaviour, including managed charging

- Understand how the development of EV infrastructure and policy can encourage sustainable mobilities

2. Research opportunities and roadmap development

Based on the literature review (the full literature review is presented in section C) a list of barriers to successful integration of EVs into the grid was generated. The barrier analysis followed the structure show in Table 1. The detailed analysis is presented in section D.2 of this report. Following workshops with the IRG, the list of barriers was narrowed to the most important and high impact areas, and then re-projected as research opportunities. The IRG further refined these research priorities, and each of the areas are summarised below. These research opportunities form the basis for developing the research roadmap.

Table 1 Barrier Analysis Classification (Dunstan, Boronyak, *et al.*, 2011)

Barriers								
Technical		**Institutional (**"non-technical"**)**						
1. Current Technology	2. Current Costs	3. Regulatory Failure	4. Inefficient Pricing	5. Payback Gap	6. Split Incentives	7. Lack of Information	8. Cultural Barriers	9. Lack of coordination "Confusion"

2.1 Summary of research opportunities

The project team conducted an opportunity analysis based on the research opportunities identified through the literature review and barrier analysis and prioritisation in the previous stage. The following is a summary of research opportunities. The research opportunities follow the same classification as the barrier analysis

1a. Impact of uncoordinated and uncontrolled charging on grid security, stability and reliability (level 1 and level 3 chargers - respective concerns). Coordinated smart charging methods could mitigate the adverse impacts resulting from uncoordinated and uncontrolled charging on grid stability and reliability. It could reduce uncertain peak demand events and would assist the grid operator operate the power grid within its stability boundaries. As uncoordinated/uncontrolled charging is strongly linked to driver behaviour, it is important to consider driver behaviour when developing coordinated smart charging approaches. There is an opportunity for developing coordinated smart charging approaches to enhance grid stability and reliability considering driver behavioural models.

1b. Safety of home charging infrastructure. Home charging infrastructure such as chargers could be the most significant single load on the household. Safety concerns depend on the charger type and how it is operated. There is an opportunity for modelling and characterisation of home charging infrastructure and investigating safety boundaries.

1c Grid integration and orchestration technology for EVs: There is a need to understand how transport dynamics and energy demand will change in coming decades due to electromobility, and in particular what the likely impacts of increased EV uptake and progressive performance improvements will be. It will be important to demonstrate how synthetic inertia can be sourced from a collection of EVs across a grid and show the potential impacts and opportunities for the

network. A key area of concern is managing grid-wide EV charging to ensure that inverters and rectifiers across the system support the network via access to the vehicle batteries. The literature observes current limitations, and it is not clear how such dynamics and demand will change as the transition to electromobility takes place. Important factors will include the level of improved EV performance and investment in associated infrastructure that will affect vehicle range, charging-time, and charging accessibility. In order to understand how EVs can be part of the electricity grid, it will be important to understand owner preferences for charging and location of vehicles. There is a need to investigate this longer-term situation, support beneficial behaviour in the transition phase, and understand what technologies can bridge current behaviour to the future state. A key research question will be which levers are appropriate to use for customer behaviour other than financial mechanisms. Urban development allied with regulations and smart-charging devices can accommodate this change.

Along with grid-to-vehicle (G2V), EVs with vehicle-to-grid (V2G) technology could unlock vehicle batteries' potential and could potentially replace, or at least significantly augment, large grid-scale energy storage. However, V2G technology could result in adverse grid impacts (e.g., overloading of transformers, cables, and feeders; rapid voltage variations), and loss of opportunity if not properly managed and coordinated. Therefore, there is a strong need to develop optimal orchestration strategies for V2G technology to capture opportunities associated with the provision of ancillary services such as energy storage and frequency and voltage control. Additionally, there is a need to develop strategies to orchestrate V2G with the existing distributed energy resources (e.g., solar-photovoltaic) integrated into a low-voltage network to capture associated opportunities and avoid risks. Focus needs to be placed on the use of regulations and smart-charging devices that provide an integrated approach to behaviour as well as precinct-scale local energy management using fit for purpose technology solutions such as blockchain systems for sharing energy and storage between users.

1d. Large / Heavy EVs and charging infrastructure availability. There is a need to develop demonstrations of electric heavy vehicles (such as on mine sites) that use microgrid recharging sites, and of electric public transport in cities to identify associated risks and opportunities. In particular, given that heavy vehicles require high-capacity charging infrastructure, such research will need to cover the following:

- Demonstrating technologies which reduce grid reliance of heavy vehicles through microgrids, storage, and onsite generation as well as large scale versions of distributed energy management systems as outlined in 1c.
- Modelling of critical national freight infrastructure and its capacity for electrification through appropriate technologies.

[Note that no research opportunities were identified under barrier 2 – 'Current Costs'. While current costs are certainly a barrier, the solutions are to conduct research and create incentives in the other areas to help reduce the cost barriers.]

3a. Lack of standards on EV grid integration. Grid code standards specify the minimum requirements of any equipment connected to the grid. Since EV chargers (both unidirectional

and bidirectional V2G chargers) are going to play an important role in grid dynamics, it is essential to set the grid code standards for EV chargers. Minimum requirements for EV chargers for grid integration need to be developed that consider their operating limits, protection requirements, and so on to assist in developing grid code requirements for EV grid integration to maintain system security, stability, and reliability.

3b. Interoperability. Within a single jurisdiction, different standards can apply for electric vehicles, vehicles-to-charger, charger-to-grid, building electricity codes, and communication interfaces. A number of international regulations are available for all charging equipment and interfaces. A detailed analysis of various standards and study on interoperability requirements is critical to determine which would be the most suitable for Australia for proper coordination of the grid integration of EVs.

3c. Regulatory and other constraints around bidirectional grid connections. There is a need to explore ways to integrate solar, urban development, and EVs into grids and analyse the requirements for adoption/integration of internationally accepted standards into the Australian regulatory landscape. Bidirectional grid connections of EV (G2V and V2G) will pose significant challenges in the regulation, economics, and stability of the grid millions EVs could be connected to many places in the grid at different times. Hence, suitable regulatory frameworks, tariff structures, smart-charging systems and grid visibility tools need to be developed and validated for the secure operation of the EV-rich grid. The role of demonstrations in urban precincts for housing and industry (especially freight logistics centres) are an opportunity for global leadership.

4a. Tariff structures, network demand, and time reflective prices for customers, bills and customer pricing. Time of use and demand/dynamic pricing policies can play a vital role in encouraging EV uptake by potentially reducing electricity costs for charging whilst also minimising unwanted grid impacts from uncontrolled wide-scale EV charging at grid-unfriendly times. Several bodies have identified pricing reform as a top priority (Hildermeier *et al*. 2019; ARENA, 2019; REVS, 2021; Graham and Havas, 2020; EVC, 2020; DISER, 2021). The opportunity here is to undertake research to understand the impact of dynamic pricing on customer behaviour, EV running costs, load profiles, and grid impacts. This should be built on existing data and current/past trials. EV tariff structures play a pivotal role in the EV charging demand placed on the power grid. Currently, network charges are the same for all customers irrespective of EV or rooftop PV. There is an urgent need to design more personalised network charges based on whether customers have EV/PV. This needs to be carefully implemented to not discourage EV uptake. There is an opportunity to design EV tariff structures to manage the charging demand on the power grid effectively and appropriate policies to facilitate the use of such tariff schemes.

4b. Understanding new business models for EVs and grids. This can relate to both consumer and industry lack of understanding of new customer-centric business models for value stacking of revenue opportunities from EVs, including the application to microgrids. An opportunity here is to increase awareness of potential benefits through business model co-design and by modelling, quantifying, and communicating the potential value that can be derived for consumers, aggregators and networks. Further research could explore various scenarios for a

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range of EV use cases that employ different charging business models with varying policy and technology options. Modelling could project energy flows and grid impacts as well as financial impacts for individual vehicle/premises and aggregations up to customer base, network topology, or geographical areas. Comparative costs and benefits to consumers for the different business models can be tested through social research and communicated across different customer typologies in terms of potential bill savings on total household energy and fuel costs. These models could be tested via demonstrations of urban development that include local integrated management systems for distributed power with electrified transport. It will be important to base research on practical demonstrations in controlled policy sandboxes to enable decision making through outcome driven findings.

6a. Value-stacking for bidirectional charging. Given the significant cost barriers to different types and scales of bidirectional charging implementations, it is important to quantify potential value streams and identify enablers so that these can be weighed against the costs (including hardware, software systems development/operation/maintenance and battery degradation). Internationally, the most comprehensive analysis of the costs and benefits of a range of vehicle-grid-integration (VGI) 'use cases' was commissioned by the California Public Utilities Commission. It concluded that there are many potential VGI use cases that can provide positive return on investment and value for money right now in the US context. Our opportunity is to undertake a study to replicate this in the Australian context to answer the questions:

- Which VGI use cases can provide value now, and how can that value be captured?
- What policies need to be changed or adopted to allow additional use cases to be deployed in the future?
- How can high and low voltage elements of the grid be balanced to ensure flexible charging patterns and timeframes?
- Where can slow charging be practical to reduce unnecessary load on the grid?
- Where do controllers fit in the new grid, and how can they complement EV adoption?
- How does the value of VGI use cases compare to other storage or DER?
- How can a charging system be organised to integrate with a DERMs package?

Examples of developing projects for electric bus depots, electric fleet centres, logistics centres, and new purpose-designed residential net zero developments can provide value-stacking data.

6b. Lack of information about the incentives affecting charging behaviour. Despite the potential for cost-reflective pricing to drive better utilisation of the grid and facilitate a smoother transition to EVs, there is a historical reluctance of residential customers to engage with ToU or demand pricing. This, combined with a lack of EVs, means that there is a shortage of information on the adoption and effectiveness of EV charging. Opportunities here include: 1) Review international dynamic pricing initiatives for EV charging with a view to developing guidelines for optimal and successful implementation in the Australian context; 2) Undertake studies to quantify the impacts of dynamic pricing on EV running costs and grid utilisation.

7a. Uncertainty on uptake forecasts (lack of data, and models relying on early adopter data). Electric vehicle uptake forecasts are vital for making informed decisions on grid upgrades and

plan and construct the EV charging infrastructure/stations. Australia is behind many developed nations in EV uptake. Australian mobility demand is comparable to parts of the USA (e.g., California) and USA data can be effectively used for informed decisions for the uptake of EVs in the Australian market. Electric vehicle forecasting models could be developed by using the data from countries with higher EV penetration.

7b. Lack of information on customer travel behaviour. It's important to better understand the travel behaviour of EV public charging customers. Research could include qualitative studies investigating the travel and charging behaviours of weekend ToUrists, as well as people who use their EV as a second or third vehicle. Public charger loyalty behaviours could also be investigated. A recent investigation by Kuby (2019) into refuelling preferences of AFV users in the US relied on surveys and GPS and card-swipe data.

7c. Lack of data access and availability. There are many data gaps, including user behaviour, load profiles, travel requirements, response to charging incentives, and physical charging infrastructure installations and characteristics (AEMO, 2021b). EV-related data such as EV uptake, charging patterns, and driver behaviour are essential for making prudent operational, policy, and planning decisions. It would be helpful to develop consistent EV-related datasets for use by industry, researchers and policy makers engaged in developing insights, products, business models, regulations etc. Through this, the research can leverage and build on existing data initiatives (AEMO), resources (NEAR), and IRENA trials (AGL). There is an opportunity to develop a data repository of EV data and subsequently to develop data extrapolating strategies using the available EV data from the other countries.

8a. Lack of understanding of charging behaviour patterns at the cultural level. The cultural dimensions affecting charging behaviour patterns among EV users in Australia are not well understood. These could be explored through analysing charging transactions, building on overseas research (Helmus *et al.,* 2020 - charging transaction data in the Netherlands; Kuby, 2019 - surveys, GPS and card-swipe data in the US). EV users could also be interviewed to investigate public charger loyalty behaviours and weekend Tourist charging behaviours.

8b. Lack of understanding of potential customer equity issues. Little information exists on potential customer equity issues in relation to EV purchase, running costs (including the impact of EV taxes) and charger access. As Hsu and Fingerman (2021) acknowledge, "adoption barriers have shaped the demographics of the early and current EV owners." This in turn influences charger placement planning (Hsu and Fingerman, 2021). Other potential equity issues relate to housing tenure and dwelling types. Investigating how DNSPs and planners could mitigate equity issues would be well-timed before widespread EV lock-in occurs.

8c. Social acceptance of bidirectional charging. Recently, Delmonte et al. (2020) undertook 60 semi-structured interviews to investigate UK EV users and potential EV-user responses to user-managed charging and supplier-managed charging. This study could be replicated in Australia to better understand bidirectional preferences and acceptance.

8d. Trust. Learning how to build trust in the aggregators/retailers/DNSPs is an opportunity. What will it take EV owners allow control for V2G; how to regulate fault protection under V2G scenario;

Provide information to understand what V2G means, education, providing information in a way that is clear and accessible. How can aggregators/retailers/DNSPs ensure EV owners are treated well, are accountable, transparent, and communicate effectively?

9a Stakeholder uncertainty. There is an opportunity to pinpoint stakeholder uncertainties around EVs, held by energy utilities, retailers, fleet operators, and OEMs. This could be investigated through qualitative analysis that gauges stakeholder perspectives on EV integration (e.g. Wolbertus et al., 2020 - Q-methodology) and where stakeholders place their role within the EV transition.

9b Transport Integrated Grids and Precincts, delivering multiple benefits while avoiding automobile dependence: There is a need to understand how energy, transport and development will interact in the future given the now inevitable shift to electro-mobility. If this is over-looked it will result in missed opportunities across all associated sectors and may cause significant risks from inaction. The opportunity to create opportunity in the nexus is provided by demonstrations of new Net Zero residential, commercial, and industrial estates being planned in cities and regions across Australia. RACE for 2030 could partner with a selection of these and enable understanding of how solar-based Microgrids can be set up that are managed locally and can integrate transport systems into them. A model for how such projects can be replicated and also expanded into surrounding suburbs could present a global first concept for the staging of Net Zero City processes. New public transport projects combined with station precinct developments with micro-mobility and 'Mobility As A Service' electric shuttles, can be used to demonstrate such opportunities.

9c Other external factors - hydrogen, storage technology. Opportunity is to model and quantify the costs and benefits across the entire life-cycle and whole national energy system, of different transport electrification futures which include different mixes of battery electric and hydrogen-powered commercial, passenger, fleet and public transport vehicles.

2.2 Research Roadmap

Based on the barrier and opportunity analysis and in consultation with the IRG, the project team developed research priorities for theme N1: EV integration into the grid. The approach for creating the roadmap was to combine the research opportunities into research projects appropriately blending the various opportunities, e.g. for the EV data focus area in the Data and Technology section, the projects combine opportunities 7c (lack of technical data) and 8a-c (addressing lack of data regarding behavioural sciences).

The table below highlights the milestones for each research priority across three timeframes: short-term (approximately the next 2 years), medium term (2-5 years), long-term (5 years and beyond). They are also colour coded to indicate the project scale (small e.g. up $100K, medium e.g. $100K-$500K, large, e.g. >$500K). Under each research priority are the impact areas that are further analysed below in section 3.2. In the Focus Area column, the research opportunities areas identified by the IRG as priorities are referenced against the opportunities listed above in section 3.1. Each research project is flagged with one, two or three *. These represent the approximate impact, with medium, high and very high represented by one, two and three * respectively. This rating system is based both on the research teams' perspectives and those of the IRG.

Table 2 Research Roadmap

Research Priorities (Impact areas)	Focus Areas (Research opportunities)	Timeframes/Milestones		
		Short term (~next 2 years)	Medium term (2-5 years)	Long term (5 years and beyond)
Data and Technology (Data repository, Network load and forecasting models)	*Charging Implications (1a, 1c)*	Understanding changing transport patterns and related energy dynamics ** (High impact)	**EV trials with whole of network approaches ***(Very high impact)**	Developing coordinated smart charging approaches **(High impact)
		Developing strategies for local governments and EV charging *(Medium impact)		
		Hardware options (e.g. advances on existing techs) **(High impact)		
	EV Uptake (7a-c, 9c)	Data studies on trend analysis and tipping points *(Medium impact)	**Improving network visibility to see EVs and EV chargers ***(Very high impact)**	Developing common load profiles based on uptake data **(High impact)
	EV Data (7c, 8a-c)	Strategies to inform customers perception of EVs and energy storage not just transport **(High impact)	Creating an independent data curator / concierge *(Medium impact)	
		Education, awareness, and customer engagement strategies **(High impact)		
Market and Pricing (Pricing models, Tariff design)	*EV Tariffs (4a, 6b)*	Understanding price sensitive demand of EVs *(Medium impact)	Tariff design and impact on customer behaviour to shift loads **(High impact)	

Est. project budget shading scale:	small e.g. up $100K	medium e.g. $100K-$500K	large, e.g. >$500K

Research Priorities (Impact areas)	Focus Areas (Research opportunities)	Timeframes/Milestones		
		Short term (~next 2 years)	**Medium term** (2-5 years)	**Long term** (5 years and beyond)
Integrated Opportunities (Interoperability, Smart Charging)	*New EV/Grid Business Models* (4b, 6a, 8b-c)	Investigating new business models for EV charging and storage in Australia (including understanding equity, social acceptance, and role of government.) **(High impact)	Demonstrating specific value streams and value stacking opportunities for bi-directional charging of EVs **(High impact)	
Integrated Opportunities (Interoperability, Smart Charging)	*Urban EV Nexus* (1d, 3c, 9b)	**Exploring regulatory and other constraints associated with the integration of energy, mobility and development** (incl. specific considerations for various types of heavy vehicles and public transport options.) ***(Very high impact)	Demonstrating how energy grids can interact with transport systems and urban development for mutual benefit **(High impact)	
Customer and Culture behaviour (Customer engagement strategy)	*Charging Patterns* (7a, 8a-c)	Behaviour studies on customer attitudes and drivers **(High impact)	Identifying hooks for messaging and engagement *(Medium impact)	
Regulatory and coordination (Technical Standards)	*EV Standards for charging* (1a-b, 3a-b)	Technical standards for bi-directional charger **(High impact)	Interoperability protocols to streamline information exchange **(High impact)	
Regulatory and coordination (Technical Standards)	*EV Standards for communication* (1c, 3a-c)	**Standards and protocols for communication ***(Very high impact)**		

Est. project budget shading scale:	small e.g. up $100k	medium e.g. $100k-$500k	large, e.g. >$500k

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2.3 Impact Planning

The impact framework is an essential component of RACE for 2030 as it enables each of its four program themes to strategically plan their research. It also provides the opportunity for those proposing projects under the themes to consider their path to impact early in the design phase and enable them to then demonstrate their impact over time.

This impact framework is designed to align with the overarching objectives of RACE for 2030 and Theme N1, whilst retaining sufficient flexibility to accommodate the diversity of projects that are likely to emerge. It is intended to:

- Guide best practice for designing projects with a clear pathway to impact such that they can demonstrate credible linkage to outcomes and impact

- Assist in evaluating and selecting research projects within the portfolio for maximising impact

- Map the Path to Impact for EVs and the Grid

The path to impact for Theme N1 follows the program logic that takes us from inputs (time, money, people, knowledge, etc.) and activities to outputs to outcomes and impacts. For projects funded by RACE for 2030, resources (grant funds, time) are used as inputs to support various project activities (tariff design, customer studies, etc.). The effectiveness of these activities depends on knowledge and technology diffusion – the reach of the knowledge sharing activities or the uptake of the newly developed product/outputs. This diffusion will seed new ideas among industry stakeholders, and this will be used to develop the market, such as implementing new industry practices or reducing barriers to vehicle-grid integration (VGI). This, in turn, can lead to wider societal impacts, such as lower bills, reduced greenhouse gas emissions and increased electricity system reliability.

As shown in Figure 1, the control over the outcomes and ability to attribute them to project activities generally decreases along this chain. Projects funded under Theme N1 can contribute to the identified outcomes. The role of RACE for 2030 will be in ensuring that the outputs and outcomes from this theme integrate with those of other related themes and relevant industry processes in order to deliver their full impact. While the representation of the impact logic is linear for ease of communication, it is important to note the feedback loop, from the desired impact to planned activities, while designing the research program.
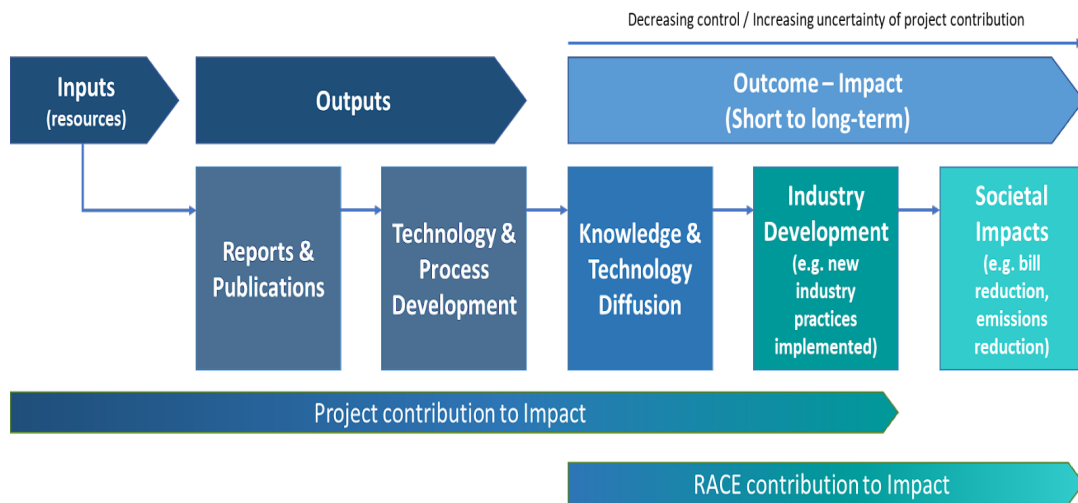
Figure 1. High-level impact framework for N1

Figure 2 provides additional detail on the impact framework specifically for Theme N1. The logic is the same, but each link in the chain is broken up further into categories. The figure also identifies indicators that can be evaluated at each stage of the chain. These categories and indicators are explained in the next section. Besides strategically planning the research portfolio at the Theme level, the framework is an impact planning and evaluation tool for projects to fit in with the Theme and RACE for 2030 impact mandate. It is recommended that projects plot their pathways to impact using the program logic inherent in the framework.

For each of these outcome and impact categories, there is at least one indicator and often several. Similarly, for each indicator, there is at least one metric, but often several. The categories, indicators and metrics are intended as a comprehensive overview of the possible industry development impacts that could flow from Theme N1. However, projects can include additional indicators and metrics where they are considered more suited to their objectives.

The framework recognises that there can be multiple pathways to impact and allows flexibility for projects to choose their own pathway(s) as illustrated in Figure 3. It links the outputs from the research opportunities with the desired outcomes and impacts seen in Figure 3. The impact areas are further linked to the research roadmap above (Table 2).

Figure 2. Detailed impact framework for N1

Figure 3. Different impact pathways for N1

B. Project Approach and Methodology

The RACE for 2030 CRC N1 theme 'Electric Vehicles and the Grid' investigates how to maximise the net benefits of Electric Vehicles (EVs) to electricity consumers, network businesses and their customers while facilitating decarbonisation of the transport sector.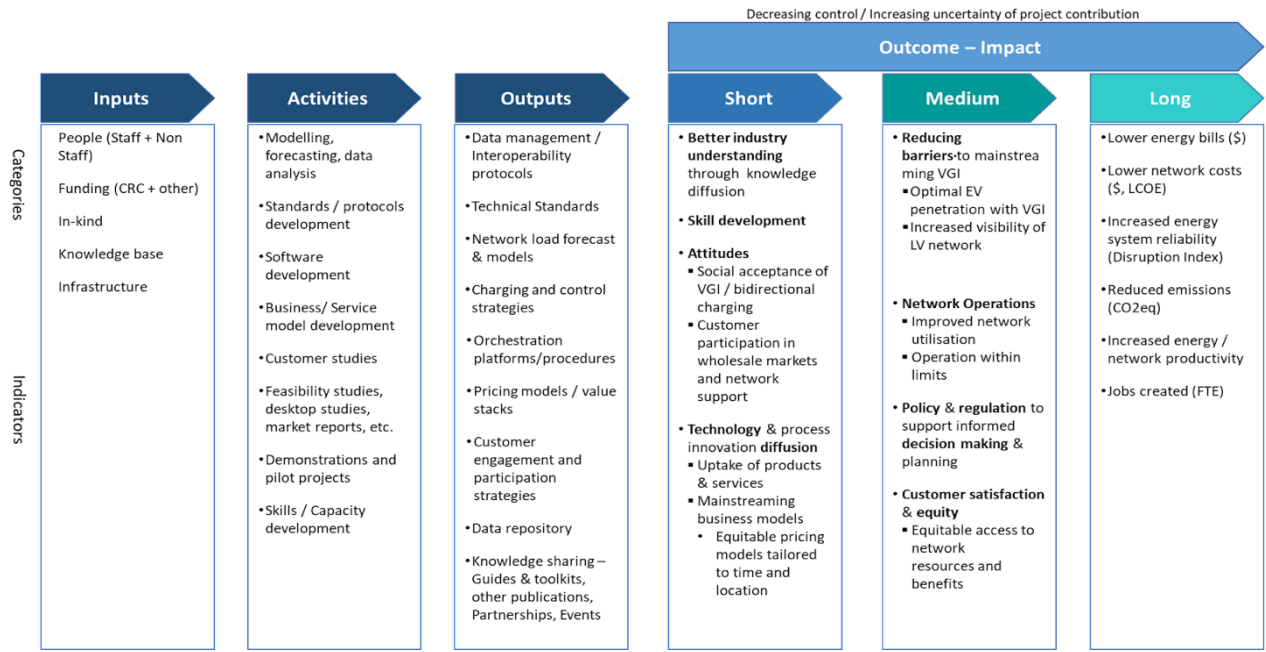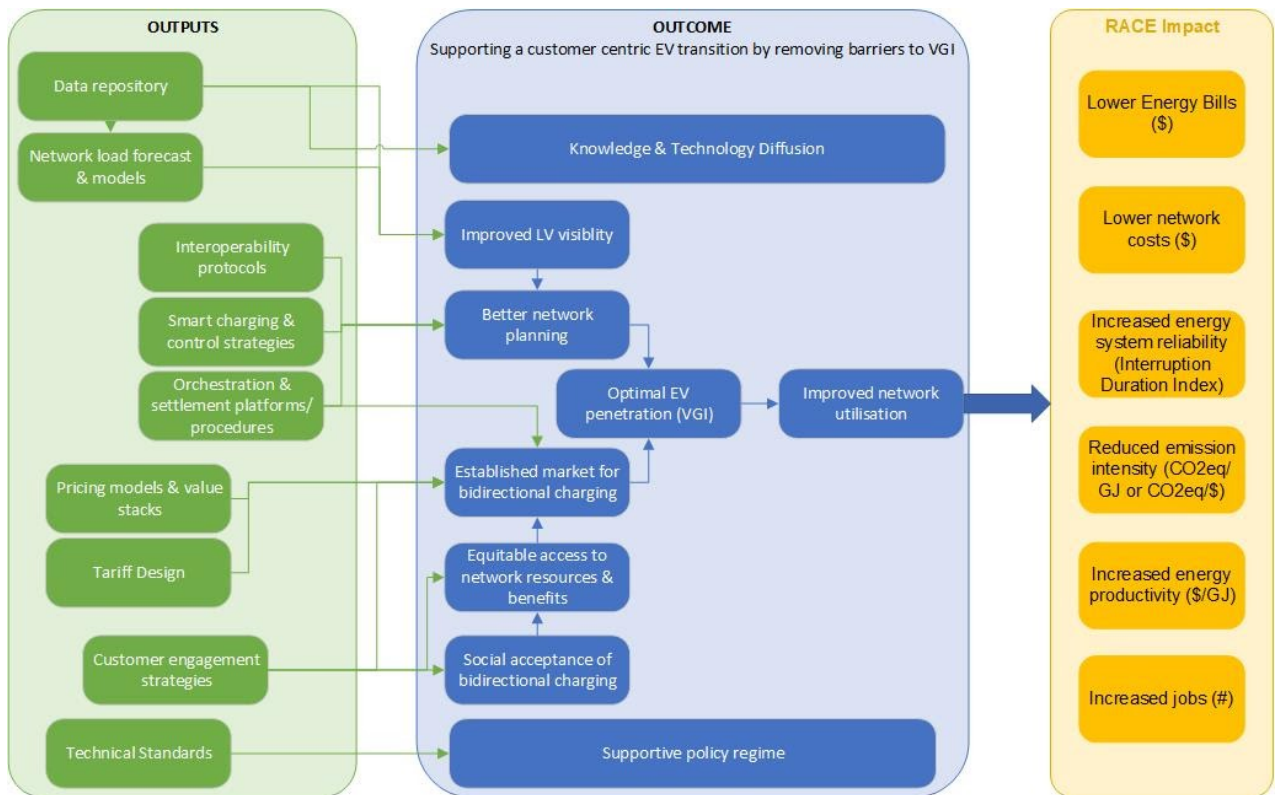 EVs are expected to become much more widespread over the next decade and some projections see EVs making up the majority of light passenger vehicle sales in Australia by 2030. The scope of this research theme extends to all plug-in electric road vehicles, including light commercial vehicles, buses, and heavy road freight. It excludes rail-based transport.

The expected rapid growth in EVs creates opportunities as well as challenges for grid integration such as their impacts on peak and minimum electricity demand. This theme will investigate the optimal deployment pathways (such as timing, capacity (kW demand and kWh), location and functionality of EV charging points) as well as arrangements for EV smart charging (intelligent management of charging and discharging) and bidirectional charging (also known as vehicle-to-grid (V2G), vehicle-to-home (V2H), vehicle to premises (V2P), or 'reverse charging').

While there is increasing customer interest in home battery storage solutions, these solutions are relatively expensive (e.g., more than $10k for 10-15 kWh), with an expected life of about 10 years. Electric vehicles in comparison are likely to have much greater energy storage capacity (40-90 kWh) per unit and in aggregate. There is an urgent need to understand EV uptake trends and pathways and how to manage their impact on the grid to minimise cost impacts and facilitate the use of this very large aggregate battery capacity to support the energy transition. This research theme will consider EVs' capacity to support the uptake of distributed energy resources (particularly rooftop PV) and to participate in smart home/business energy management. It will also investigate opportunities to support the integration of large-scale renewable energy such as wind and solar.

Preliminary analysis indicates that even a modest increase in EVs and public fast charging can, if not coordinated, strain the capacity of electricity substations. Optimised integration could convert this potential adverse impact on the grid into a significant opportunity. This opportunity assessment aims to:

- Synthesise current research addressing the barriers as well as enablers of integrating EVs into the grid. It is critically important that the uptake of EVs leads to benefits for electricity networks and the customers that pay for the infrastructure. A poorly rolled out EV sector will result in higher prices, sub-optimal investments, and lower carbon emission reductions. The research agenda produced from this work will generate projects that will result in pathways that are optimal for networks as well as EV owners.

- Identify the potential EV uptake pathways and commercialisation opportunities, in particular those that could lead to investment opportunities in Australia.

- Examine how EVs and urban infrastructure interact. Electrification of mobility does not stop at simple light passenger and light commercial vehicles but has the potential to impact on vehicle ownership trends, use of public transport, and large-scale changes in how we build and use our cities.

This opportunity assessment project was conducted in four stages:

- Stage 1: Establishment of an industry reference group (IRG) to provide input and feedback the research team

- Stage 2: Review of Australian and international literature to produce discussion papers on barriers and opportunities to EVs' integration to grid

- Stage 3: Consultation with industry experts (IRG and others) to get deeper insights into risks and barriers to the electricity and EV sector as well as research opportunities and key metrics for research impact

- Stage 4: Synthesis and road mapping, concluding with a project finding report and knowledge sharing forum

The stages are described in the following subsections.

1. Establishment of the Industry Reference Group (IRG)

Industry Reference Group establishment was the first main activity of the RACE 2030 Electric Vehicle Opportunity Assessment project. The IRG plays a critical role in the project success and will be responsible for providing input and feedback to the project scope and guidance over the project duration. It has been a key vehicle for the qualitative and consultation part of the study.

The IRG is made up of representatives across the whole value chain (retailers, DNSPs, manufacturers, start-ups, consumer organisations, government) and is led and chaired by the Electric Vehicle Council and Ultima Capital. Additional industry representatives joined in a consulting capacity to ensure industry representations across both the strategic consultation (industry reference) group (IRG) and the delivery team. The approach to establishing the group was as follows: 1) Each RACE CRC partner involved directly in the development of the proposal was invited to help identify suitable participants aligned with the proposed structure of the IRG (see above). 2) The EV Council led the scanning and mapping of the suitable IRG members in consultation with the project team and will be responsible for their recruitment and onboarding process. 3) The EV Council served as an Independent Chair of the IRG, with a co-chair from a network or consumer interest point of view.

The process to manage the Industry Reference Group includes:

- IRG Meetings were chaired by IRG chairpersons with a defined agenda and facilitated by the project leader.
- All documentation was provided with suitable notice prior to the meetings, and all reporting requirements from the CRC were incorporated into the IRG meeting agenda. IRG members were asked to participate in follow up surveys to enable the collection of information and opinions on specific topics. This qualitative input complemented the qualitative entries from workshops and other IRG discussions.

The IRG formation was successfully coordinated and confirmed at the inception meeting (see below). At the outset, a total of 16 organisations were represented, each by 1-5 people. The IRG had a good balance of consumer representatives, policymakers and regulators, city planners and urban infrastructure representatives (public transport etc.) and electricity supply chain industry. IRG member organisations are shown in Table 3 below.

Table 3. List of IRG members

AGL	Ausgrid	Jemena	Starling Energy
AEMO	Chargefox	Tritium	Horizon Power
NRMA	EV-NRG	Vicinity	NSW Planning
Nissan	FBICRC	ANU	Western Energy
Startup Bootcamp	EA Technologies	EPRI	DELWP

The inception meeting was conducted on 12th March 2021 to meet with and establish the IRG members and confirm the IRG's role. The meeting was led by the IRG Chairs, Behyad Jaffari (EV Council) and John Frick (Ultima), and facilitated by the project leader Roger Dargaville and the UTS project delivery team. Project team members were also present in the meeting.

Meeting outcome: The desired meeting outcomes were for everyone to be clear on their role, the research agenda, and to get to know the project team and other IRG members. As part of the meeting, IRG members were also asked about their aspirations for the project. Initial recommendations for research focus include customers behaviour and preferences, industry trends, uptake predictions, least cost integration, charging optimisation, and harmonisation at the global scale.

2. Literature review and discussion papers

The research team conducted a review of Australian and international literature (peer-reviewed institutional publications and grey literature) to produce two discussion papers for discussion at the IRG on the following topics:

- Identification analysis of barriers to uptake of EVs (i.e., access to charging infrastructure) and barriers to sub-optimal performance of EVs in relation to the grid (i.e., tariff structures that fail to avoid charging load at peak times; lack of a framework for enabling V2G under circumstances such as extreme demand)
- Identification of opportunities based on the barriers to uptake of EVs identified in Workshop 1

The discussion papers were presented to the IRG and its members' responses were collated for further desktop analysis, including cost/benefit analysis and scenario analysis.

The scope of the literature review was divided into four areas. The review of each area was led by the university project teams (RMIT, UNSW, Curtin University) and CSIRO. The areas were –

- Techno-economic assessment of market and technology trends/practices (CSIRO)

- EV-grid impact assessments, policy, regulatory framework, and standardisation (RMIT)

- Urban design and distributed grid management (Curtin University)

- Social science research for EVs (UNSW)

The Monash Team was tasked with compiling and synthesising the areas of the review into discussion papers (appended to this report). To manage resources and citations, a literature review register and a full reference list were established.

3. Qualitative studies

Input was sought via a consultation process with IRG and nominated international experts (UK and US representatives). The delivery team conducted two workshops with the IRG members to get deeper insights into the following two areas:

a. Risks, barriers and priorities for the electricity sector and EV sector in the upcoming 10 years

b. Commercial and research opportunities of EV uptake in relation to the grid

Each workshop was followed by a short online survey of IRG members to capture individual perspectives.

3.1 First workshop: EV and grid barriers (UTS-lead)

A one and half hour virtual barriers workshop was held on 22nd April 2021. The objective of this workshop was to present the barriers identified through the literature review and to seek feedback on industry priorities and risks from workshop participants.

Project leader Dr Roger Dargaville presented the findings of the research so far in the barriers discussion papers. The aim of the workshop was to invite feedback through breakout sessions and the first breakout session focussed on:

- Feedback on the list of barriers shared
- Identification by IRG of any new barriers not identified through the literature
- Industry prioritisation of barriers in the short, medium, and long term

The second breakout session focussed on understanding the impact that resolving these barriers would have on the electricity sector and the influence RACE for 2030 could exert in this process. Participants plotted their identified barriers using interactive software to arrive at a collective group priority.

Overall, the workshop participants agreed with the list of barriers captured and there was broad consensus among the groups on what constituted technical and institutional barriers. However, some disparity became apparent in the temporal aspects of these barriers. A barrier analysis is presented in Section D.

3.2 Second workshop: EV and grid opportunities (UTS-lead)

A second one and half hour virtual workshop was held on 19th May 2021, this time with the objective of presenting the opportunities identified through the literature review and barrier analysis and to get feedback on industry priorities.

Once again, Dr Roger Dargaville (Monash Uni) introduced the workshop and presented the status of the research so far. Dr Scott Dwyer (UNSW) shared the barrier analysis and the translation to solutions and opportunities; Kriti Nagrath (UNSW) presented the impact framework and the key outcomes and indicators for the research theme. The aim of the workshop was to invite feedback through the breakout session. It focussed on –

- Capturing opportunities and project ideas from the IRG
- Prioritising the opportunities that industry would invest in

Feedback was elicited from IRG members on potential research projects that could be undertaken with collaboration between industry and research organisations (universities, CSIRO, etc.) to maximise the benefits of EVs for distribution networks. Overall, the workshop participants agreed with the high-level list of opportunities captured.

4. Synthesis and road mapping

The outcomes of the literature review, desktop analysis, and qualitative consultations were synthesised in the final report, which was then presented to IRG for feedback and comments. The team will seek a final evaluation of the project experience and deliverables from IRG in the final survey.

C.Literature Review

Electric vehicles (EV) are seeing significant growth and adoption in many parts of the world because of their superior environmental impact and reduced running costs compared to internal combustion engine (ICE) vehicles. Social concerns for a sustainable future combined with policies adopted by various governments to phase out fossil fuel-based vehicles are also driving greater market demands for electromobility options. Consequently, these factors are creating an increased penetration of electric vehicles into power grids and this is likely to cause a significant impact on grid operations over the next several decades. Even at today's low EV penetration levels in Australia, knowledge sharing regarding the grid impact of EVs is essential to enable the transition to a high-EV penetration state and avoid detrimental outcomes.

This section provides a review of literature and the state of the art of EV uptakes, its integration and impact on the grid. The review is reported in the following four areas:

- Techno-economic assessment of market and technology trends/practices
- EV grid impact assessments, policy, regulatory framework, and standardisation
- Urban design and distributed grid management
- Social science research for EVs

1. Techno-economic assessment of market and technology trends/practices

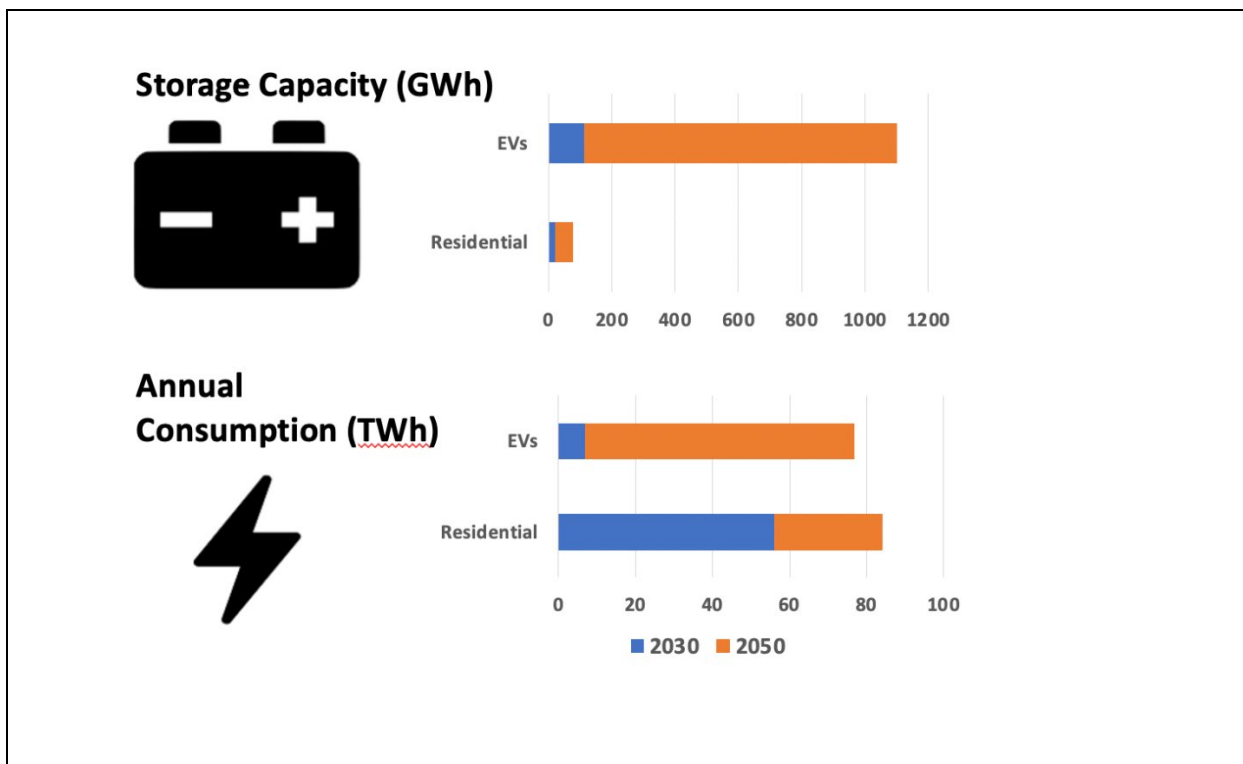**Figure 4. Summary Statistics taken from ABS and AEMO data sources.**

Figure 4 shows projected storage capacity of EVs and home batteries in 2030 and 2050, indicating that the capacity in EVs will be much larger than home scale batteries, with massive growth from 2030 to 2050. For energy consumption, EV use will be modest in 2030, but will grow to be comparable to the total residential sector (AEMO, 2020a)

1.1 Current and Projected Market Snapshot

1.1.1 Passenger EV

Plug-in electric passenger vehicle sales are on a trend of significant growth globally, with over 2 million sales in 2019 representing 2.5% of all new vehicles sold and an annual increase of 9% from the previous year. In Australia, the EV market is currently much softer, with sales of battery EV and plug-in hybrid electric passenger vehicles (PHEV) in 2020 at 6900 units representing 0.7% of total new vehicle sales of around 1 million (Electric Vehicle Council, 2020). Annual growth in EV sales in 2020 in Australia was quite volatile, partly due to the low numbers of vehicles sold overall. Sales growth in 2020 slowed to 3% after a tripling of sales between 2018 and 2019.

According to the Electric Vehicle Council (Electric Vehicle Council, 2020) –

- Australians currently have access to 28 electric vehicle models from 11 different carmakers (12 battery electric and 16 PHEV). This is significantly fewer than other comparable markets globally, including other right-hand drive markets.
- Eight of these vehicles are priced under $65,000.
- By the end of 2021, we expect to see six new electric vehicles on the road in Australia – five of these will be battery electric vehicles, and one plug-in hybrid. Two of these will be under $50,000.
- Australia's limited model availability and softer market is restricted by an unsupportive policy environment with no fuel efficiency standards or national electric vehicle policy.

The full range of EVs currently and imminently available in Australia is outlined in DISER (2021). Barriers and enablers of consumer attitudes to EVs are already very well documented (Dunstan, Usher, Josh, *et al.*, 2011; Lutsey, 2015; ClimateWorks, 2016; Electric Vehicle Council, 2020) and primarily concerned with considerations of total costs of ownership, range (battery capacity), convenience of refuelling, and access to charging infrastructure (home and public).

CSIRO (Graham and Havas, 2020) has modelled the future uptake of electric vehicles for AEMO. This includes battery-only PHEV and Hydrogen options across passenger vehicles, light commercials, trucks, buses, and motorcycles. The study considered constraints including access to home and public charging infrastructure and modelled five scenarios: Slow Change, Central, Fast Change, High levels of DER, and Step Change. These scenarios are listed in order of increasingly optimistic assumptions around economic growth, energy efficiency, growth of renewables and EV infrastructure/tech developments. The share of projected electric vehicle sales by scenario are shown in Figure 5, and a breakdown by vehicle type is shown in Figure 6.

The CSIRO projections have been adopted by AEMO as they are considered to be among the most credible independently generated projections available. The range of uncertainties they cover in the different scenarios modelled is considered to be broad and representative enough to enable sensible energy policy development. CSIRO's projections are therefore used in this assessment as the basis for any necessary projections of the Australian EV market.

As the most recent update from the Electric Vehicle Council has shown (Electric Vehicle Council, 2020), a significant portion of car makers globally will be phasing out the manufacturing of ICEs completely over the next 10-20 years. It is clear that in future EVs will be a widely adopted mainstream technology. However, as CSIRO's projections show in Figure 5, the timing, speed, and extent of the transition to EVs in Australia is still uncertain. Uncertainty also remains about the Australian policy landscape, where, unlike in similar markets internationally, the federal

government position is that subsidising EV purchases does not represent value for money from an emissions reduction perspective (DISER, 2021). In contrast to this, several state jurisdictions are introducing various mixes of purchase incentives and road user charges for electric vehicles (Electric Vehicle Council, 2020)

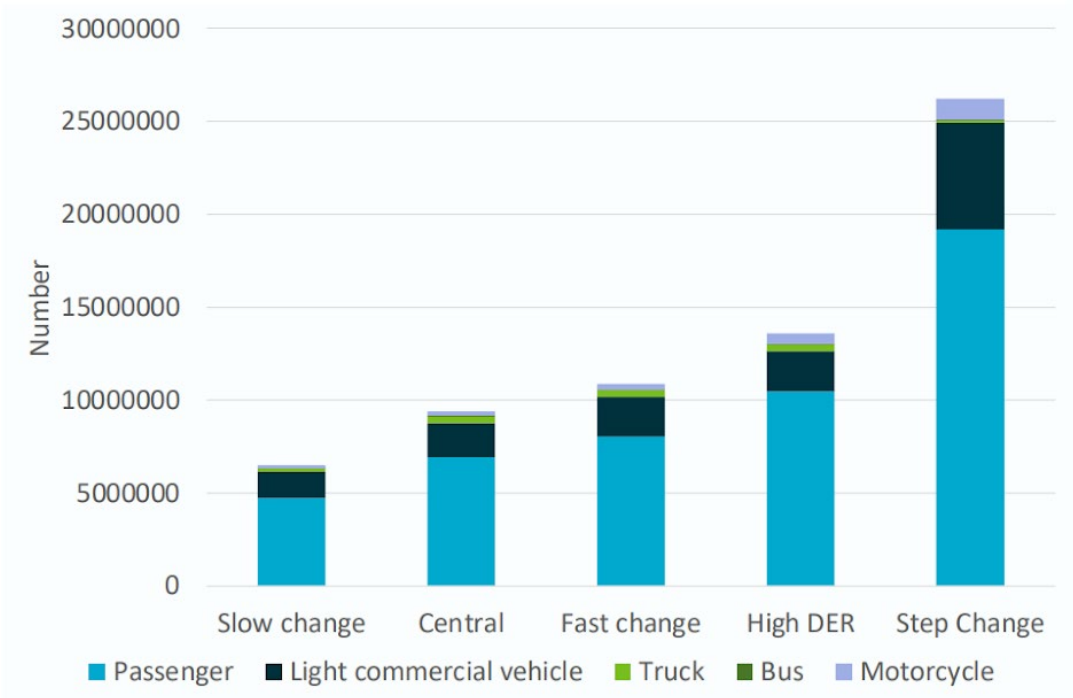**Figure 5. Electric vehicle sales share by scenario (Graham and Havas, 2020)**

Figure 6. Electric vehicle sales share by vehicle type (Graham and Havas, 2020)

1.1.2 Commercial EVs

Global commercial vehicle stock was estimated to be around 400,000 vehicles in 2019, with the potential to grow to over 40 million vehicles over the next decade (IEA, 2020). Currently, only a limited number of electric commercial vehicles are available in Australia, and current stock is largely unknown. According to the EVC, several global manufacturers have indicated an intention to supply the Australian market in the future. The Australian electric automotive technology company SEA Electric estimates that the total market in Australia is 20,000 electric commercial vehicles per year across all classes. SEA Electric has sold 105 converted vehicles, primarily to councils, refuse management services, and last mile delivery services (Electric Vehicle Council, 2020).

Barriers to commercial EVs:

- Australian Design Rules (ADRs) and heavy vehicle regulations that make commercial EVs less attractive in Australia than in other markets (Electric Vehicle Council, 2020) or effectively not saleable (e.g., due to more restrictive width limitations).
- The additional weight of required batteries, which reduces the cargo capacity and increases delivery costs/kg.
- High pricing for high-capacity connections and stationary batteries for grid supplementation at fast charging stations at hubs, depots, and rest stops.
- The fast charging requirements for heavy vehicle EVs, which can potentially exceed 350kW per vehicle.

Opportunities for commercial EVs:

- A battery-electric drivetrain provides the most energy efficient pathway for freight decarbonisation (excluding direct electrification, e.g., via rail).
- Delivery services, including short-haul logistics, last mile and parcel delivery
- Capital costs are falling due to declining battery prices. When combined with reduced fuel and maintenance costs, battery-electric can be cost competitive with ICE in many applications; this will expand over time as charging time, charging cycles, and economics per kilogram are improving rapidly.
- Stationary batteries that are trickle-charged on low-capacity connections can be used to bolster grid connections at rest stops to enable very rapid charging. NREL (National Renewable Energy Laboratory, US) is currently developing a megawatt-scale charging system for medium and heavy duty electric vehicles, enabling drivers to charge in less than 30 minutes at reasonable cost (Toner and Heinen, 2018).
- Long haul opportunities for charging can be designed around mandated rest stops. Scania is building a strategy around this: "In a few years' time, Scania plans to introduce long-distance electric trucks that will be able to carry a total weight of 40 tonnes for 4.5 hours and fast charge during the drivers' compulsory 45-minute rest." (Holland, 2021).

1.1.3 Electric Buses

Globally, there are roughly half a million buses currently in use. Most of these operate in China, where several city centres have fully electrified bus fleets. This figure is projected to rise to between 2.6 and 4.1 million buses globally over the next decade (IEA, 2020). Air quality concerns in densely populated cities, as well as carbon emissions reductions, are key drivers of a move

towards electric buses in many markets around the world. Currently in Australia, electric buses are primarily operated in trials, although several governments and private sector operators have made commitments to bus electrification.

Electric bus trials have been in train for several years. Recently conducted or current trials are underway in NSW, VIC, WA, ACT, and QLD. A comprehensive summary of recent electric bus trials and commitments is provided by the Electric Vehicle Council (Electric Vehicle Council, 2020).

Among the most significant Australian initiatives are the NSW Government's plans for up to 100% electrification of the bus network as part of the Government's commitment to achieving net zero emissions by 2050. Transport for NSW has developed a Zero Emission Bus Strategic Narrative which sets out that over 4,000 buses and 38 depots require transition to electric or hydrogen, and that "Battery Electric Buses are approaching cost parity with diesel on a whole-life-cost basis, suggesting transition can commence now." (T4NSW, 2020). In terms of the Australian market potential, the Electric Vehicle Council (2020) notes that –

- There are currently 100,473 buses (mostly ICE) operating in the public and private sectors, with bus trips accounting for 5% of public transport journeys.
- Approximately 1,300 new heavy buses are registered each year in Australia.
- Commercial availability of electric buses is increasing in Australia, and suppliers include BYD, Carbridge, Gemilang, Precision Buses, Volgren and Yutong.

Electric bus battery capacities can vary from around 60kWh to more than 500 kWh, with larger sizes needed to service long routes or long charging intervals (Gao, Lin and Franzese, 2017). They generally require very high-capacity chargers (up to 500kW), which invariably requires upgrades to electricity networks (Gao *et al.*, 2017). However, as for commercial vehicles and unlike residential charging infrastructure these chargers are planned in tandem with utilities.

Although electricity system upgrade is clearly a cost and often considered a barrier to uptake, analysis for the NSW Government has indicated that grid upgrade costs are actually only a small fraction of the total transition costs to fully electrified buses because of the very high investment required in the vehicles (T4NSW, 2020). Bus electrification could therefore provide a financially advantageous driver for necessary grid upgrades for the electrification of broader industry and help remove barriers for other transport electrifications, including commercial and passenger vehicle fleets.

Barriers to bus electrification include:

- Range – battery-electric not yet capable of covering 100% of routes, especially under variable topography and weather.
- To accommodate charging infrastructure, depots and routes will require more space for chargers as well as onsite electrical works and potential grid upgrades.
- Buses travel a lot of kilometres during their life and compared to passenger vehicles have limited opportunities for charging and discharging.
- Depot charging is currently concentrated into hubs and primarily required at night, away from solar generation times and often aligned with network peaks.
- Opportunistic en-route charging can align with solar generation but is expensive.

Opportunities for bus electrification:

- Buses are in service for long periods of time per day and over their lifetime (25 years). Capital costs are falling due to declining battery prices, and when combined with reduced fuel and maintenance costs, battery-electric can be cost competitive with ICE in many applications; this will expand over time as charging time and charging cycles improve.
- The cost of potential grid upgrades required to electrify bus fleets is only a small fraction of the capital cost of the bus fleet upgrades (T4NSW, 2020).
- Available storage capacity in buses is very large and concentrated, providing niche opportunities for night-time V2G without orchestration overheads required for distributed vehicle fleets.
- Bus electrifications can provide significant benefits in terms of air quality and noise reduction in densely populated areas.

1.1.4 Bikes, Scooters, and Motorbikes

Globally electric two and three-wheeled vehicles represent the majority of the electric vehicle fleet and is concentrated in China, India, and the ten countries of ASEAN (IEA, 2020).

Electric bicycle, scooter, and motorcycle usage is increasing in Australia with the availability of an increasingly large range of product offerings (Electric Vehicle Council, 2020). Increased demand for delivery drivers/riders for last mile delivery, and various government policies and urban initiatives around micro-transport, are also encouraging increased uptake and usage of electric options.

The energy and power requirements of two-wheeled EVs are negligible compared to larger EVs because of their smaller battery sizes, which are typically in the range 0.5-10 kWh and heavily skewed towards the smaller end. In Australia, where uptake of these EVs is projected to be small compared with other vehicle types (Graham and Havas, 2020), the direct impact on electricity grids is therefore likely to be very small. However, if the uptake aligns more with what is expected in Asian cities, enough trips taken on more efficient two-wheeled EVs may displace some of the passenger and commercial EV trip usage over time, or facilitate greater public transport usage. This may have some second order impact on the electricity system.

1.2 EV-Grid Integration Technologies, Practice and Trends

1.2.1 Broad EV impacts on national electricity market

As outlined above, while there is uncertainty about the adoption curve for electric vehicles, there is little debate that they will ultimately play an important role in the future of mobility and the energy system.

The wide scale uptake of EVs presents both challenges and opportunities for utilities and grid managers. Under an unmanaged future scenario, uncontrolled EV-charging could lead to network congestion and exacerbation of peak loads, particularly on the medium and low voltage network; this network could require augmentation under this scenario. Because EVs are a mobile source of load with magnitude dependent on travel requirements of the users, new data and tools will be required to better forecast travel and charging demand at fine spatial scales that are compatible with the MV and LV network impacts. On the other hand, under a more managed future scenario, energy stored in EVs that is excess to requirements could be used to provide grid support services and direct value to users by storing renewable energy and time shifting

demand. This is made possible physically because vehicles typically spend about 95% of their lifetime parked (IEA, 2019) and technologically by emerging bidirectional and managed charging technologies. The Australian Government Future Fuels Strategy has identified integration of EV's into the electricity system as one of its top five priorities (DISER, 2021).

Current deployment of EVs across the electricity market comprises less than 1% of vehicles (Electric Vehicle Council, 2020). AEMO/CSIRO forecasts ('Central' scenario) project that the uptake of EVs across the NEM will reach 3%, or half a million vehicles, by 2029-30. As shown in Figure 5, this is forecast to accelerate from 2030 as more choices of cheaper EV models come online and recharging infrastructure availability increases. The proportion of vehicles assumed to participate in 'coordinated' EV charging arrangements such as virtual power plants, V2G and V2H that optimise vehicle charging for demand and/or market conditions is also projected to accelerate from 2030 onwards.

When compared to other sources of demand on the electricity system, AEMO's 2020 Electricity Statement of Opportunities (AEMO, 2020b) predicts that EVs will be the fastest growing sector of energy demand across the National Electricity Market (NEM) from the mid-2020s.

This accords with predictions for Western Australia. Under the 'Central' scenario, electricity demand from EVs is forecast to add approximately 1TWh of new consumption to the NEM each year from the late 2020s. Figure 7 shows projected demand from EVs under the 'Central' uptake scenario relative to other sources of consumption. It shows that the additional level of demand from EVs will approach total residential energy consumption by 2050, and that total demand is projected to rise above the historical peak levels from 2010 in around 2045. In the medium term (10-20 years), EVs are projected to be the main driver of a return to growth in operational energy consumption and maximum demand as rooftop PV and energy efficiency investments tail off due to market saturation (Graham and Havas, 2020).
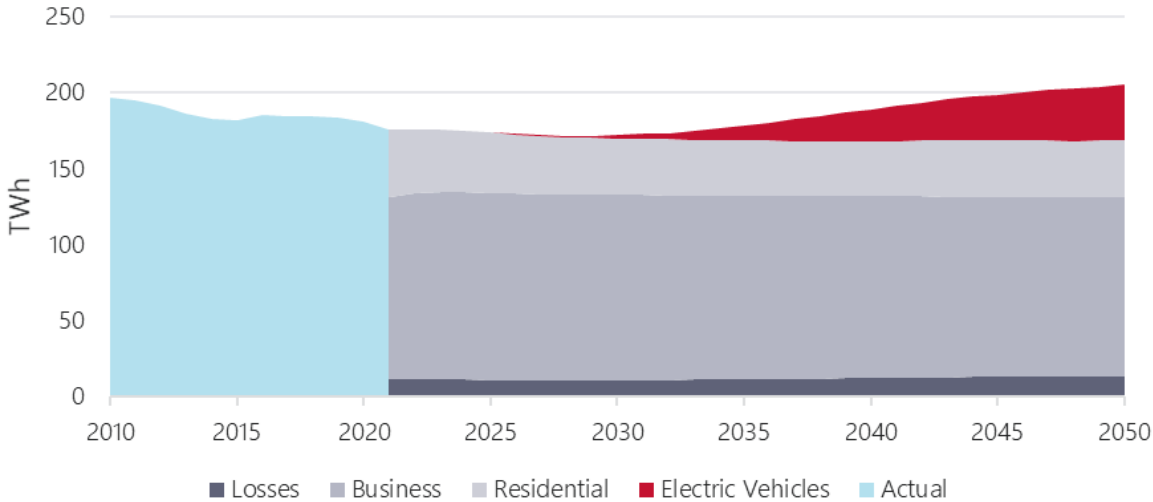
Figure 7. NEM operational consumption, ESOO 2020 Central scenario (AEMO, 2020b)

The impact this extra demand will have on the electricity grid is unpredictable due to uncertainty around uptake levels and the level of mitigation provided by managed charging.

The My Electric Avenue project in the UK has projected a doubling of the residential after-diversity maximum demand from around 1 to 2 kW when EV market share reaches 40% –70%

(See Figure 8). The study also determined that if this extra demand were extrapolated nationally, widespread grid augmentation would be necessary, with up to 32% of low voltage networks requiring intervention (EA Technology, 2016). More detailed analysis of grid impacts of EVs in the Australian context is provided in Section 2.2 of part C .
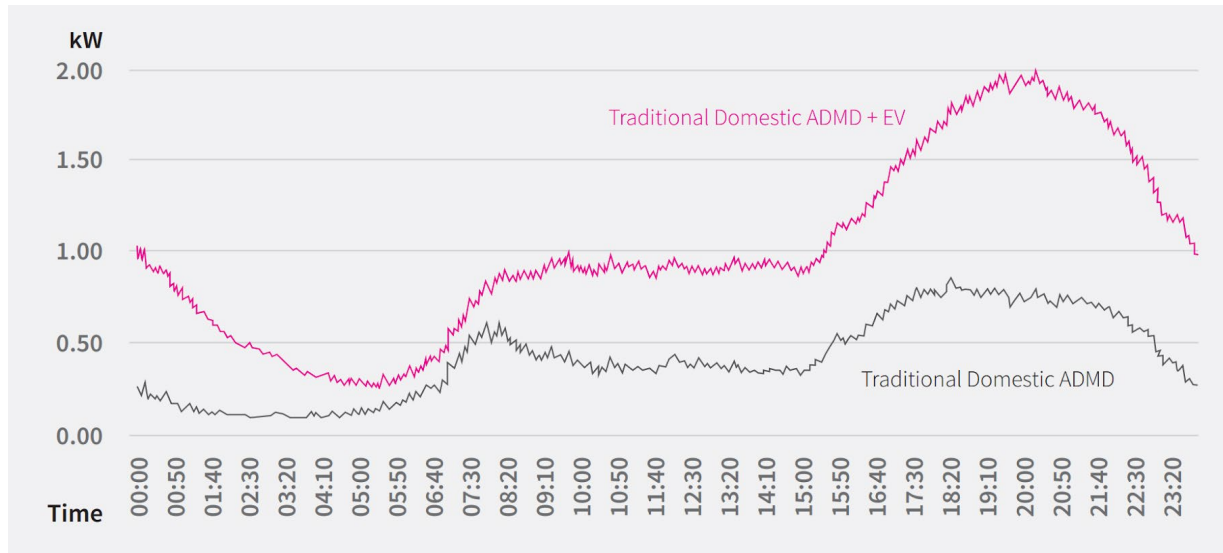
Figure 8. Electric Nation predictions of domestic ADMC with and without EV charging (EA Technology, 2016)

The DEIP EV Grid Integration Working Group has outlined that the time of day that EVs charge or discharge will be a major factor in future EV-grid integration costs (AEMO, 2021b). From a whole system perspective, if large numbers of EVs are charging during peak demand periods in the late afternoon, expansive augmentation of network and supply capacity may be required to ensure this extra energy demand can be met. However, if EV charging can be shifted toward the middle of the day during times of peak solar generation, they may actually provide benefits to the broader energy system by mitigating minimum energy demand challenges, increasing network and renewables utilisation, and providing flexibility for use of renewable energy stored in EV batteries for V2G/V2H opportunities.

Due to the high uptake of solar PV installations on residential rooftops, minimum demand thresholds are now starting to be exceeded in some jurisdictions where PV panels have to be switched off to ensure grid stability (ABC, 2021). This will be an increasing trend in the medium term until broader market saturation comes into play (Graham and Havas, 2020). Although this is a challenge for utilities, the emergence of EVs that can be charged during daytime hours presents a potential win-win solution and opportunity to increase the market for solar PV.

Given that power requirements for EV charging can be comparable to the typical power demand from a residential household, whenever large numbers of EVs are charging or discharging their impact on system stability at distribution or street level is also something that needs to be understood, and this is addressed further in Section 1.3.

Projected electric vehicle load profiles for passenger vehicles in Australia are shown in Figure 5 (Graham and Havas, 2020). These are averaged values for the whole of Australia based on an adapted UK study (Roberts, 2016). The profiles include charging behaviours based on –

- Convenience – uncontrolled charging primarily on arrival at home

- Night – controlled off-peak charging

- Day – extensive public charging and solar availability

- Fast/Highway – simulated fast/highway charging and traffic volumes

The average national charging profiles for commercial vehicles developed by CSIRO are shown in Figures 5 and 6 and have been derived from available Australian studies (Mader and Bräunl, 2013; Victorian Government, 2013).

Given that passenger vehicles are expected to dominate the EV landscape, the most likely point of concern is passenger vehicle convenience charging. The projected demand profile under this scenario has maximum load aligned with peak demand times and is also out of sync with solar generation. Light commercial vehicles are the second largest segment of the EV market, and although the charging demands are higher per vehicle, the vehicle numbers and shape of the modelled profiles indicate that impacts on the electricity system are of less concern given that charging is primarily spread through the day and does not encroach on evening peaks. As would be expected, heavy trucks have much larger projected charging demand, but as vehicle numbers are small impacts will be largely localised to hubs/depots and designated rest stops and so potentially more manageable from an electricity system standpoint.
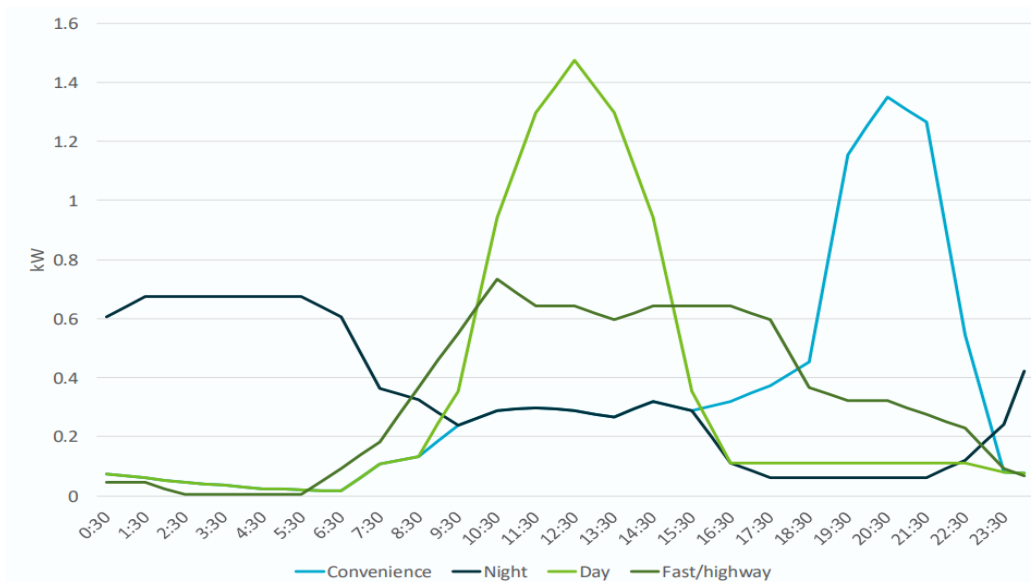

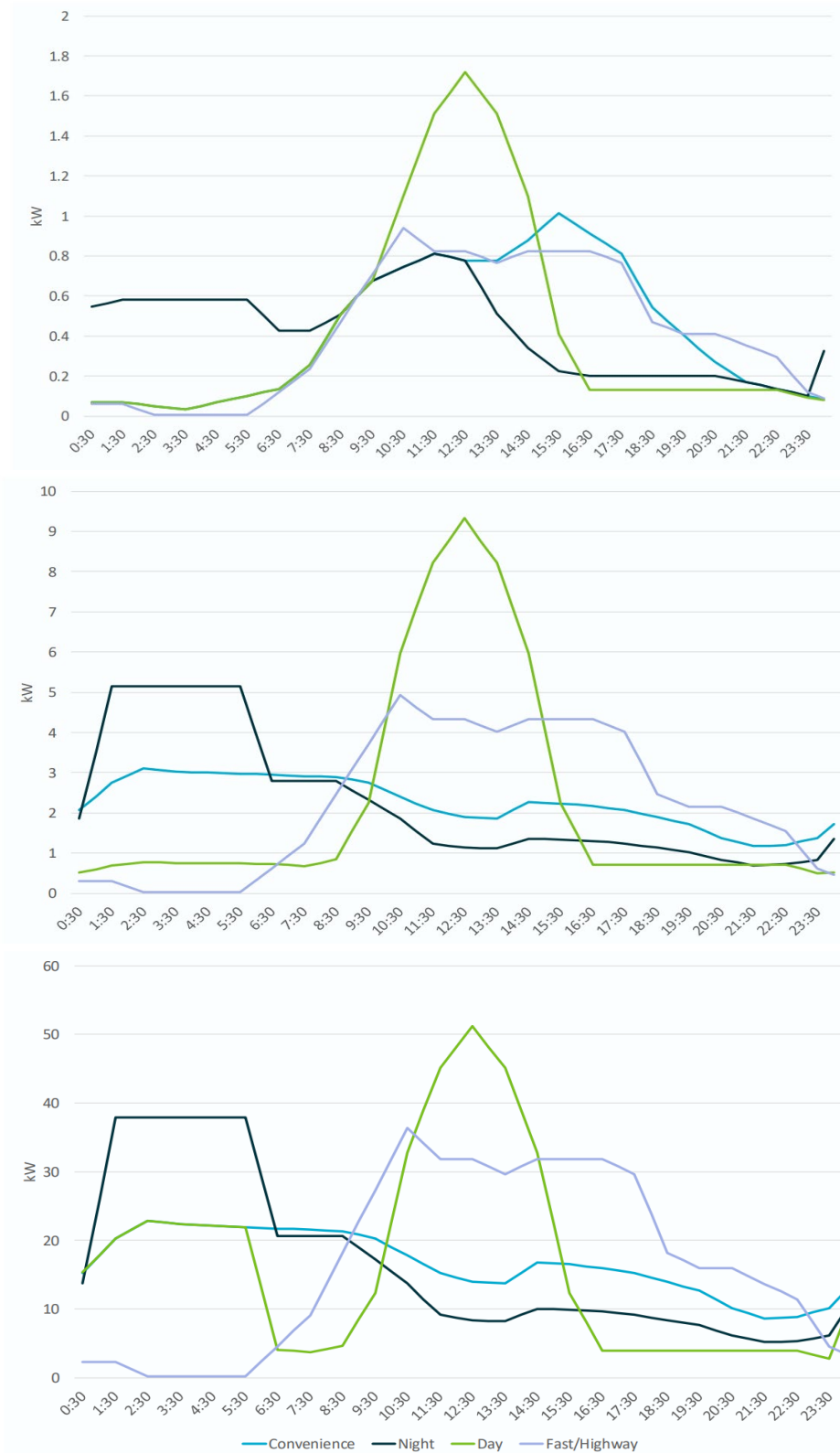**Figure 9. Average passenger electric vehicle charging profiles (Graham and Havas, 2020)**

Figure 10. Average commercial electric vehicle charging profiles
from top to bottom: Medium-sized light commercial vehicle; Rigid truck; Articulated truck (Graham and Havas, 2020)

Key barriers and opportunities for the broader electricity market:

- Load growth from EVs could equal residential sector consumption over time
- Convenience charging of EVs coincides with peak loads
- Uncertain uptake forecasts: Unpredictable speed and extent of uptake creates uncertainty about the extent and type of grid integration investment and actions required. This is critical as investments and research priorities depend on understanding how many EVs there will be, where, and how they will be used. Uptake forecasts ranging from 5M to 20M EVs in Australia represent vastly different futures for mobility and the grid at either end of that spectrum.
- Managed charging could mitigate minimum energy demand challenges, increasing network and renewables utilisation, and provide flexibility for using energy stored in EV batteries V2G/V2H opportunities

1.2.2 Storage capacity potential in EVs

According to IRENA (IRENA, 2019), more than 1 billion EVs could be on the road around the world by 2050 if most of the passenger vehicles sold globally from 2040 onwards are electric. IRENA analysis indicates that the future global EV battery capacity could dwarf stationary battery capacity. The projection is that in 2050 around 14TWh of EV batteries would be available globally compared to 9TWh of stationary batteries.

In the Australian context, based on current projections it is possible that EV battery storage capacity will be somewhere in the order of five to ten times the size of stationary battery capacity installed on the grid and behind-the-meter at residential and commercial premises. This is based on projections of somewhere between 6M and 12M vehicles on the road in Australia by 2050 (Graham and Havas, 2020) and an assumed EV battery size around 30 kWh. This equates to an additional annual electricity consumption in the range of 13-26TWh and a total EV battery storage capacity in the range 180-360GWh (Graham and Havas, 2020). Installations of stationary batteries in commercial and residential premises will consume somewhere between 10 and 45 GWh by 2050. In terms of utility-scale storage, AEMO has projected that between 6 and 19 GWh of dispatchable storage will be required by 2040 (AEMO, 2020a). So even while allowing for significant uncertainties in the projections, the outlook for Australia is that EV storage capacity will be significantly larger than stationary battery capacity in the long term. To put this into scale, the total daily energy consumption on the NEM is around 500GWh. This means that the daily consumption in the residential sector is around 120 GWh (AEMO, 2017) and that storage capacity in EV batteries could theoretically meet residential demand plus potentially more than 50% of total demand.

Table 4. Projected storage capacities in 2050

Storage Type	Projection – lower (GWh)	Projection – upper (GWh)
Utility-scale	6	19
Commercial	1	5
Residential	10	40
EV	180	360

Key barriers and opportunities around EV energy storage potential:

- EV energy usage could approach, and potentially exceed, residential consumption under highest uptake scenarios.
- Size of storage capacity available can meet significant levels of demand, significantly exceeding total residential consumption even under moderate uptake scenarios.

1.3 Charging Infrastructure

International review studies covering more mature EV markets than Australia such as Norway and California indicate that the vast majority of EV charging takes place in homes. This is especially the case in markets where high levels of home charging opportunity exist, as is the case in Australia. Figure 11 below (Bedir *et al.*, 2018) shows the modelled breakdown of charging location by time of day for 1.3M vehicles (or roughly 10% EV uptake) in the Californian market in 2025. The modelling is based on 24-hour daily driving schedules, sales projections, vehicle/charger attributes, and spatial analysis. The study predicts that the bulk of charging will take place overnight using L1 and L2 chargers in residential homes on all days. Workplace charging with demand concentrated during the morning is significant on weekdays while public L2 and fast charging becomes significant on weekends, with demand spread fairly evenly throughout the day.

Public charging and fast charging become more important in environments with limited off-street parking at homes/workplaces and a higher share of long driving distances along national highways (Funke *et al.*, 2019). Research of international markets by Energia (Energia, 2018) has shown that "… public charging infrastructure was a necessary but not sufficient factor in PEV adoption. In other words, the lack of public charging infrastructure will hold back PEV adoption, but it will not by itself drive greater levels of PEV adoption."

Bedir et al. (2018) project to support 1.3 million PEVs by 2025, California will need the following charging infrastructure:

- Home charging: One charger at every detached home with an EV
- Multi-unit dwellings: One charger for every 10 EVs on the road
- Work/Public destination charging: One charger for every 10-13 EVs on the road
- Public fast charging: One charger for every 50-150 EVs on the road

If we use the same ratios as a guide for charging infrastructure requirements in Australia, in 2030 – assuming 2.5 million EVs (step Change scenario, AEMO 2020a) – we will require the following:

- Home charging: One charger at every detached home with an EV
- Multi-unit dwellings: One charger at least for every building
- Work/Public destination charging: roughly 200,000
- Public fast charging (50+kW: roughly 15,000 chargers

According to the EVC (Electric Vehicle Council, 2020), the current status of public charging infrastructure in Australia is as follows:

- 357 fast chargers at 157 locations (over 50 kW)
- 2000 standard chargers/1200 locations (less than 50 kW)
- Many more under planning

The Australian Government's Future Fuels Strategy states that its highest priority is the roll out of EV charging infrastructure where it is needed (DISER, 2021). AEMO (2020a) has recommended the urgent development of an access-controlled EVSE (Electric Vehicle Supply Equipment) data register, which would include location and characteristics of all EVSEs on the grid to help inform network modelling and forecasting. Without this, much of the installed hardware operating behind the meter will remain invisible to networks.
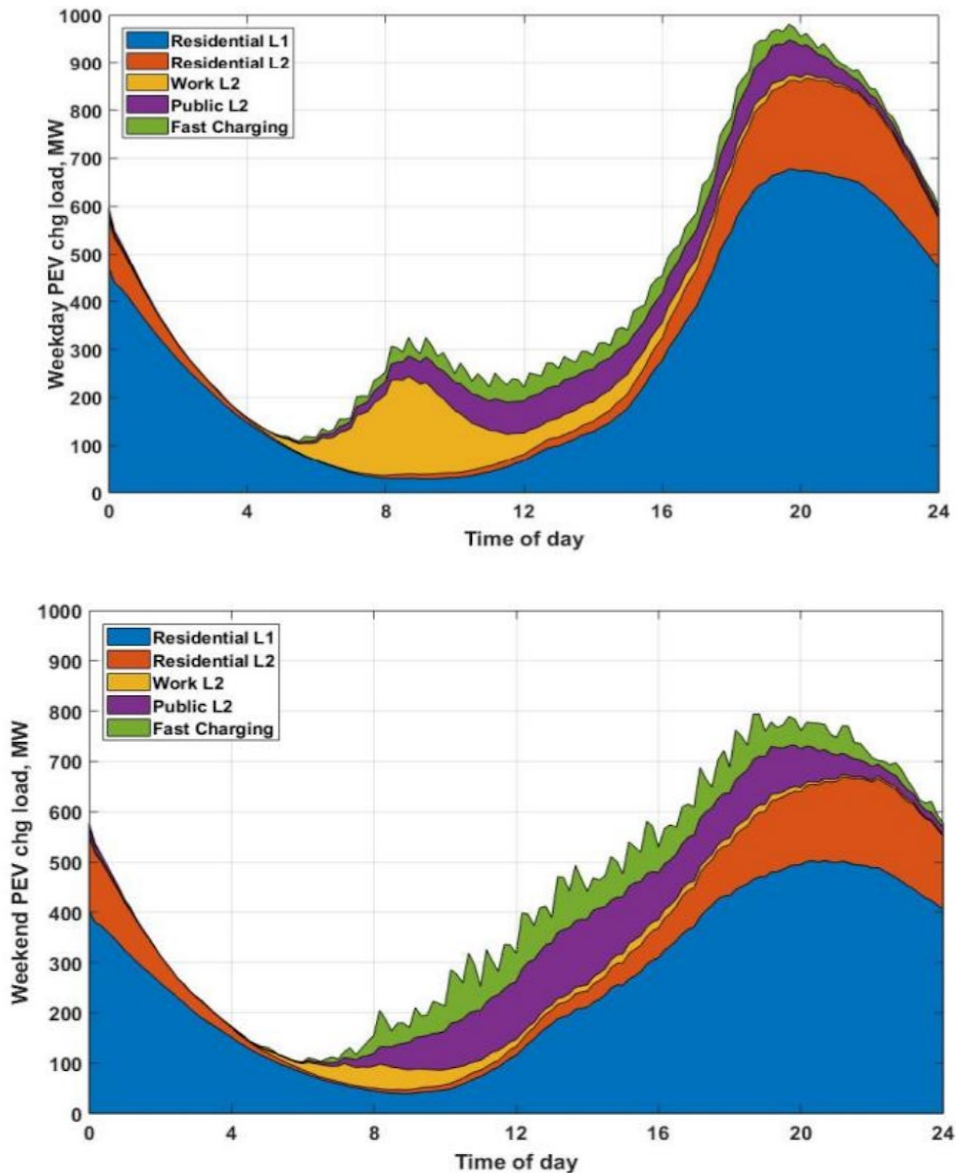
Figure 11. Projected EV charging profiles for California in 2025 (Bedir *et al.*, 2018)

Key barriers around public charging infrastructure:

- Costs of smart, bidirectional, or grid-interactive L2 chargers is currently higher than standalone non-networked chargers (see later sections)
- Installation/connection costs and regulatory hurdles for both electrical connection and planning approvals for installation of public infrastructure (note that this barrier also exists for commercial premises and multi-unit dwellings)
- High-powered fast chargers can be a very large load and therefore sometimes require significant grid upgrade costs, even if they are only used in short bursts.

- Energy costs - commercial tariffs are structured around very high-capacity connections, but unlike many commercial operations operating on these tariffs, for EV charging the capacity is only used for a small amount of time.

One way around the high energy costs and requirement for grid upgrades for high-capacity chargers is to install solar PV and stationary batteries to supplement the grid capacity and provide short but infrequent sessions of high-powered charging.

1.3.1 Future Charging Infrastructure Technologies

Combined management of building loads and site storage/generation and EV charging at multi-unit dwellings and workplaces can potentially reduce EV impacts on the electricity system. Large buildings often have spare grid connection capacity and thermal storage. This can be coupled with stationary storage and onsite PV and exploited in clever ways to cater for EV charging without major grid upgrades. In one example, international NREL researchers coupled a 50kW fast charger and a 40kWh battery to a building energy management system. Results indicate that the system successfully alleviates the load increase spurred by EV fast charging and also provides surplus energy to the grid to mitigate capital expense over time (NREL, 2021). High-powered highway charging infrastructure coupled with stationary storage and PV can also be useful for reducing loads on the grid (CSIRO, 2021).

Wireless in-road charging infrastructure is another future technology currently under investigation in some settings internationally (European Commission, 2018). This technology can potentially be used for convenience and constant connection either for in house parking or as a static in-road charging option for off-street parking. Dynamic in-road charging options for drive-while-charge and V2G while driving are also possible. In-road costs are of the order of $3-6M per km of road, and maintenance costs are estimated at 2.5-4 times higher than regular roads (European Commission, 2018; Schmidt, 2021). Major incentives from the government and a new set of business models are required to make in-road dynamic charging attractive (European Commission, 2018).

1.3.2 Tools for Siting and sizing of EV charging infrastructure

Selecting siting and sizing for EV charging infrastructure involves determining the most suitable location and EVSE capacity among potential options. The core objective is to maximise utilisation while minimising cost. This is a complex challenge that involves trade-offs between multiple conflicting criteria to meet to multiple objectives. Factors that need to be considered span economic, commercial, technical, social, environmental, and regulatory considerations.

A wealth of academic studies across the literature looks at various mathematical and optimisation techniques to determine EVSE siting, utilising methods and techniques based on multi-criteria decision making, multi-objective optimisation, genetic algorithms, swarm optimisation and fuzzy logic (Cai *et al.*, 2014; Lam, Leung and Chu, 2014; Guo and Zhao, 2015; Song, Wang and Yang, 2015; Andrenacci, Ragona and Valenti, 2016; He, Kuo and Wu, 2016; Zhu *et al.*, 2016). While some of these studies take detailed characteristics of electricity grid and transport networks into consideration, others use much simpler criteria.

Many of the academic studies focus on selecting preferred zones or districts for EVSE installation (Philipsen *et al.*, 2016; Wu *et al.*, 2017) and some are designed to choose between a set of predetermined alternatives (Wu *et al.*, 2016; Zhao and Li, 2016). However, some more recent studies have also utilised advanced GIS techniques and spatial analysis to freely determine precise locations at much finer spatial resolutions (Erbaş *et al.*, 2018; Dong *et al.*, 2019; Guler and Yomralioglu, 2020).

Fewer studies have developed analytical methods that inform both EVSE placement and sizing in combination. Awasthi et al. (2017) and Zhang et al. (2019) used swarm optimization methods to determine sizing as well as location. He et al. (2018) also used swarm optimization as well as linear programming methods and incorporated driving ranges of electric vehicles, which were shown to impact EVSE sizing.

Practical decision tools for EVSE sizing and siting that incorporate the sophisticated algorithms presented in the academic literature do not appear to have been developed into usable products or tools. However, some generalised and simple tools do exist. In one example, some of the more detailed considerations of electrical network and transport network characteristics have been incorporated into general electrical system modelling tools. Synergi Electric is an electrical simulation tool that can be used by utilities or charge point operators to inform intelligent EVSE siting based on electrical grid, traffic, and demographic data (DNV, 2021). An overview of the tool is shown in Figure 12 and an example output in Figure 13 Although the tool does not include all of the complex layers of factors or sophisticated types of algorithms outlined in the academic literature, it does include the effects of EV charging on the grid, which can potentially be used to assist decision making around EV siting and sizing. The charging potential assessment tool includes scenario-based calculations of EV uptake increases for individual communities, and the resulting demand for charging infrastructure.

More locally in Victoria, a simple spreadsheet-based decision tree tool has been deployed as an output from the 'Charging the Regions' project commissioned by the Central Victorian Greenhouse Alliance on behalf of a large consortium of Victorian Councils (Ndever Environmental, 2020). This tool was designed to provide general guidance to help select EVSE installation sites that would maximise benefits and keep costs low. The Network Opportunity Maps has new EV Infrastructure layers added (EV charger locations; EV registrations by postcode; traffic volume etc.) The project was undertaken by ISF and funded by the New South Wales Government.

Key benefits of the optimisation of charge-point sizing and location include:

- Utilities will have greater certainty and better visibility of likely future siting and sizing of EVSEs on their networks, enabling smoother and smarter integration.

- Charge-point operators have increased and more reliable asset utilisation and potentially better return on investment, and reduced risk.

- Drivers experience greater convenience due to optimal locations and minimal charging costs due to optimal sizing and minimal capital investment costs.

- Car manufacturers are provided a better line of sight on market suitability for products, potentially leading to higher EV sales figures.

Key barriers to optimised charging infrastructure tools include readiness of planning schemes, constraints around site access and grid connection, and installation hurdles. In terms of opportunities, while there is a lot of research on developing methods and algorithms for informing decisions on optimal EVSE siting and some on sizing, it is difficult to find any practical tools that have been developed for use by industry. If the industry's needs in this area can be captured and synthesised, then some of these existing technologies may be suitable to apply in the development of practical tools.
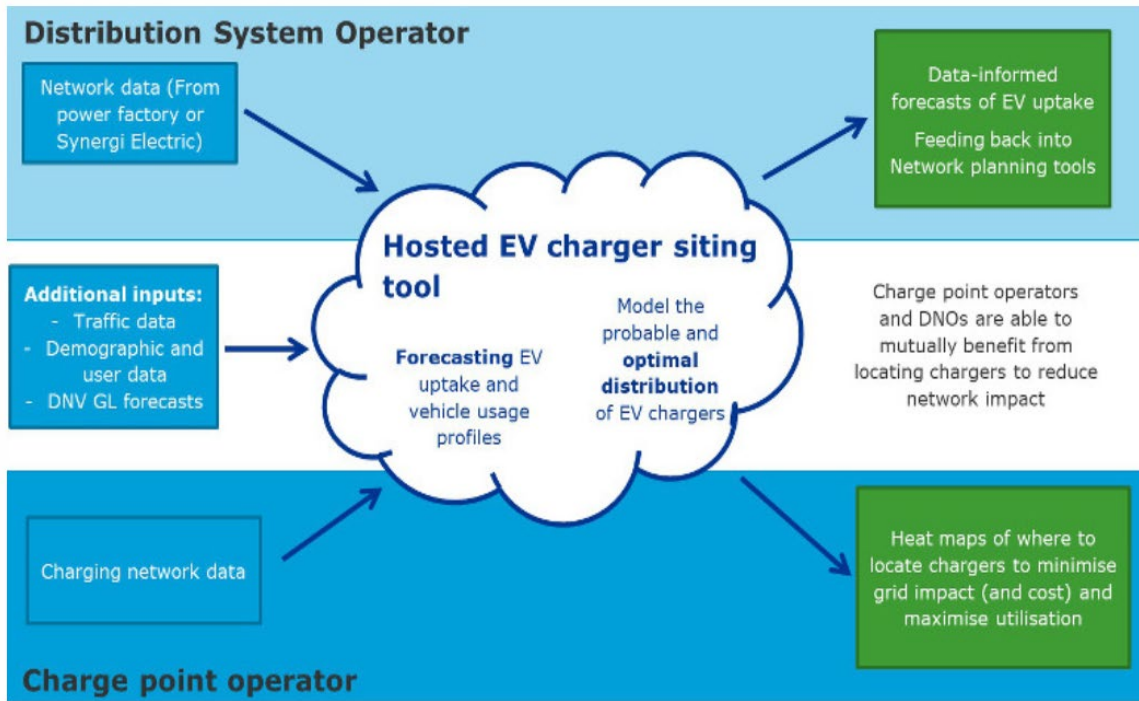
Figure 12. Overview of Synergi Electric EVSE siting tool (DNV, 2021)

Figure 3 Distribution system grid congestion

Figure 13. Output from Synergi Electric EVSE siting tool. Red = Distribution grid congestion (DNV, 2021).

1.3.3 ToU tariffs and dynamic pricing

Currently in Australia, a significant majority of residential customers are signed up to electricity plans on flat tariff structures. These comprise an infrastructure component of around $0.80 to $1.20 per day of connection and a usage fee of around 20 to 30c per kWh used, regardless of the time of day/week/year. Customers with installed PV often have an additional tariff rate to cover feed-in for solar exports.

Residential customers in some states have an additional discounted 'controlled load' rate which has historically been used exclusively for electric hot water systems but is now being marketed towards use for EV charging:

- In Queensland, Ergon has an EV energy plan to encourage Queenslanders to charge electric vehicles during the day, when renewables form the greatest part of the energy mix. On 'Tariff 33', power is available for a minimum of 18 hours each day. The times when power is switched off on this Tariff may change from day to day and vary in duration as determined by Ergon (Ergon Energy, 2019).

- Western Australia's state-owned electricity retailer, Synergy, is launching a trial in which it will offer households an ultra-low daytime electricity tariff of 8c/kWh in a bid to help soak up the state's abundant rooftop solar energy supply (Vorrath, 2020).

Business customers are more likely to be connected under ToU or demand tariffs. Time of use tariffs include different consumption rates per kWh at different times of day/week/year; demand tariffs generally combine discounted ToU charges with additional 'dynamic' charges to cover connection costs and are adjusted according to the maximum amount of power draw from the grid (e.g., in $/kW per day).

Time of use and demand/dynamic pricing policies can play a vital role in encouraging EV uptake by potentially reducing electricity costs for charging whilst also minimising unwanted grid impacts from uncontrolled widescale EV charging at grid-unfriendly times. While many electricity retailers in Australia offer ToU and demand tariffs to their residential customers, the uptake is currently low and variable across the country at somewhere between 0% and 20% of customers depending on location.

According to Hurlbut et al. (2020) ToU can be a powerful tool to manage residential EV load, but it can also have the potential to create new or secondary peaks if not managed carefully (see Figures 14 and 15 below for real world examples). If managed well, pairing ToU with demand response or direct utility control of EV charging can provide even greater benefits, which will allow utilities to unlock the higher value benefits of managed charging.

Several real-world trials have tested EV owners' willingness to shift charging behaviour through pricing incentives; some of these are outlined and synthesised in Appendix 2. In a recent example, Octopus EVs in the UK has shown the effectiveness of price signals in shifting behaviour, where the use of their 'Agile Tariff' resulted in customers reducing their peak-period consumption by 47% (Cook, 2019). The Electric Nation Project in the UK has shown that time-of-use pricing incentives can result in peak load reduction from EV charging of nearly 50%, resulting in annual energy cost savings of around $240AUD (Electric Nation, 2019). The charging load profiles with and without pricing incentive from this trial are shown in Figure 14. This shows the changed behaviour driven by incentivised pricing - a slight increase in peak, but shifting forward

a few hours. Data from the EV project in the US (US Department of Energy, 2014), which deployed more than 8000 vehicles across 18 cities, is reproduced in Figure 15. This shows an even more pronounced change in charging behaviour between cities with flat electricity pricing compared to San Diego, which had a ToU tariff with lower rates beginning at midnight, resulting in a large spike in EV charging demand after that time.

Despite the potential for ToU pricing to drive better utilisation of the grid and potentially a smoother transition to EVs by price-incentivising off-peak consumption, Stenner et al. (2015) have suggested that there are no policies (as of 2015) which would substantially increase uptake of ToU or demand pricing in the residential sector. Graham and Havas (2020) have concluded that under the current situation, given the historical reluctance of residential customers to engage with ToU or demand pricing, the prospects for greater residential adoption of these are considered low. This is potentially problematic for a future with wide scale EV uptake as it has been shown that expected demand/convenience charging of EVs will exacerbate existing peak loads and waste the potential opportunity to soak up excess solar generation (Graham and Havas, 2020)
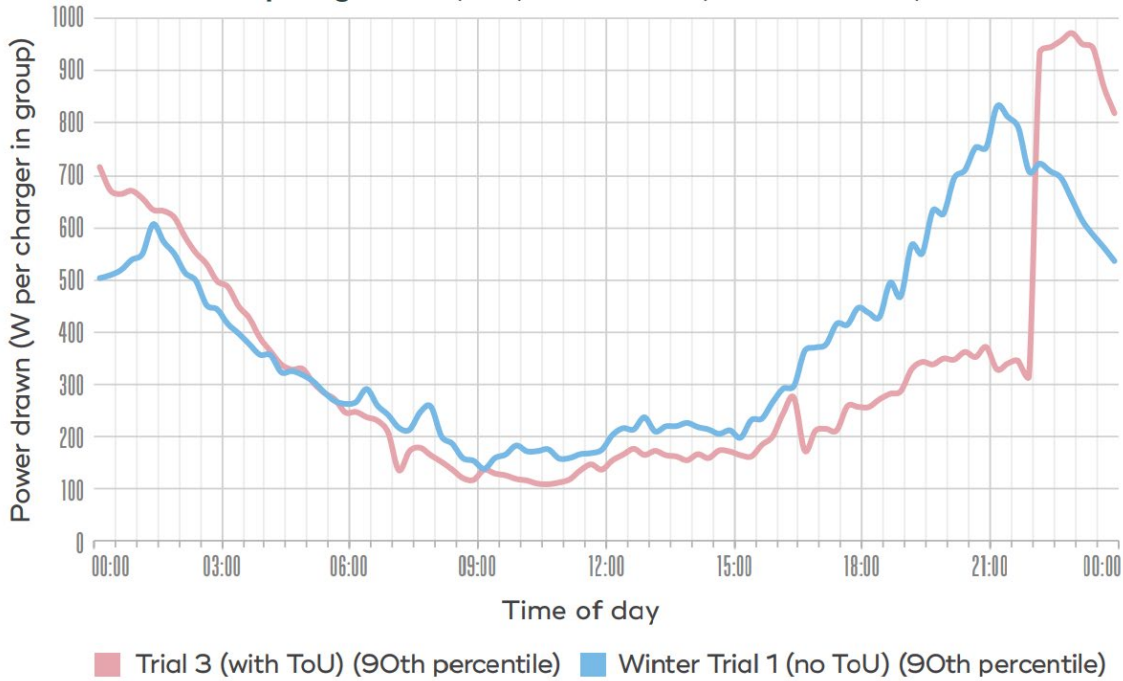
Figure 14. Electric Nation Smart charging trial – charging demand with and without a simulated ToU tariff (Electric Nation, 2019)
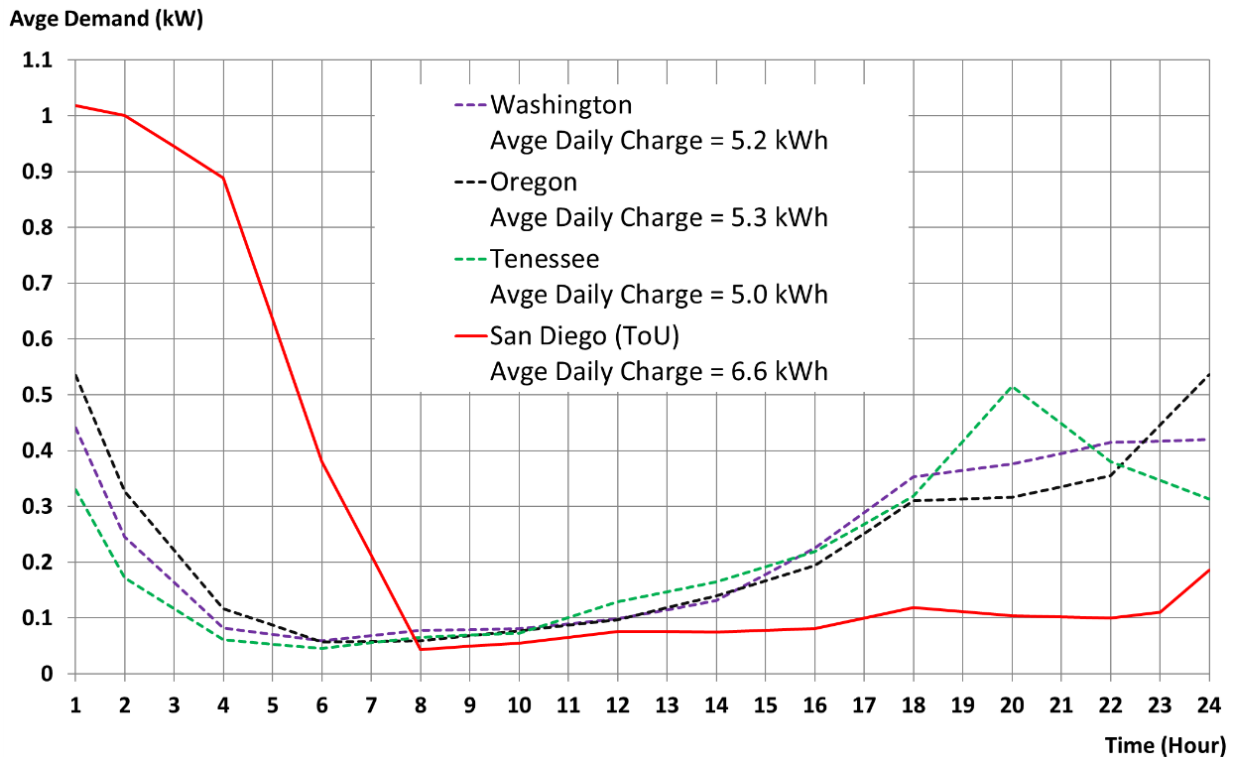
Figure 15. Comparison of unmanaged charging profiles versus ToU charging in San Diego for the EV project (adapted from DOE, 2014, and Paevere *et al.,* 2014)

1.3.4 Academic Literature on price-incentivised EV charging

Many examples of research in the academic literature have focussed on optimising EV charging through various pricing incentives such as ToU tariffs or dynamic pricing. These studies can be roughly categorised by the key objectives of the pricing incentives being analysed. These are related to –

- Cost minimisation to EV owners/operators (Mohsenian-Rad and Leon-Garcia, 2010; Anderson and Rutherford, 2014; Martinenas *et al.,* 2015; Misra, Bera and Ojha, 2015; Chen *et al.*, 2017)

- Peak load reduction (Cao *et al.*, 2012; Soltani, Kim and Giannakis, 2015; Bitencourt et al., 2017; Latinopoulos, Sivakumar and Polak, 2017)

- Grid stability, transformer overload, and power quality (Lopes, Soares and Almeida, 2009; Deilami et al., 2011; Binetti *et al.*, 2015; Dubey and Santoso, 2015; Hajforoosh, Masoum and Islam, 2016; Chen *et al.*, 2017; Korolko and Sahinoglu, 2017; Maigha and Crow, 2017; Soares et al., 2017)

The academic literature as sampled above is focussed mainly on theoretical solutions to simulated or modelled scenarios. This is to be expected given the limited amount of real-world data available and hence necessitates analysis based on synthetic or derived data. The breadth of knowledge, methods, and techniques that have been developed in the literature to model and optimise the impacts of different pricing incentives are impressive. Based on the modelling, clear theoretical evidence exists that incentives are effective if behavioural assumptions around EV driving and charging behaviour/preferences hold true. However, there appear to be very few

examples of translation of these methods into practical tools for use by industry, and also little evidence that the real world trials that are testing price-driven incentive programs have drawn on the sophisticated models and methods developed for academic research to any large extent so far. A key opportunity in this space is that, once further data are available from real world trials currently underway, recently completed, and undertaken as part of the RACE for 2030 EVs and the Grid Research Roadmap, then the theoretical methods and models can be validated, refined, and put to greater use in optimising EV-grid integration.

1.3.5 Pricing policy priorities

Several studies and industry-led initiatives have highlighted incentivised EV-charging pricing policy as one of the highest priority initiatives needed to enable a smooth transition to grid-integrated EVs. Examples include:

- A global review of smart EV charging practices (Hildermeier *et al*., 2019) concluded that time-varying electricity pricing can motivate electric vehicle drivers to charge at times that are advantageous for the electricity system. It also showed that ToU tariffs can deliver economic value to EV owners in the order of €150 per annum.

- The International Renewable Energy Agency has identified as high policy priority the implementation of time-of-use tariffs, eventually followed by dynamic prices for EV charging, to allow EVs to participate in ancillary service markets and enable value stacking (IRENA, 2019).

- The Vehicle Grid Integration Working Group in California, USA (California Public Utilities Commission, 2020), has identified various reform of retail rates toward ToU pricing as among its highest priority policy recommendations.

- The REVS project (Jones *et al.,* 2021) has recommended the implementation of real-time and ToU pricing options as an immediate action to encourage EVs to minimise constraints and maximise opportunities through integrating EVs into energy systems.

  It specifically recommends a staged implementation as follows:

  i. In the short term, expanded use of ToU energy and demand tariffs can shift EV charging outside of peaks.

  ii. As bidirectional charging and aggregation becomes more widespread, dynamic, and localised price signals can manage congestion more actively.

- Graham and Havas (2020) have identified that any tariff incentives for EVs that shift load to the daytime period will be highly beneficial in the long term due to the increasing amount of solar generation projected to come online.

- The Electric Vehicle Council in Australia (2020) has identified commercial electricity tariff reform as essential in removing barriers to the rollout of fast charger networks across Australia. Current operating costs for public charging infrastructure are affecting the viability of public fast charging operators and act as a barrier for rolling out further infrastructure. Although fast charge infrastructure can require very large capacity grid infrastructure, its load profiles are completely different to the commercial/industrial connections for which the tariffs and cost recovery economics are designed. Often, these

tariffs are in fact 'over-recovering' the true electricity supply costs of fast chargers. To address this, it is essential that data on fast-charger utilisation and its impacts on electricity networks are collected and analysed to ensure that future EVSE tariff designs are reflective of true supply costs. This can then flow down to users through transparent pricing options that will help to minimise supply costs and usage charges for fast charging in the long term.

- The DEIP Grid Integration Working Group has identified as a priority a taskforce on 'Residential Tariffs and Incentives' as well as on 'High-capacity Tariffs' that includes consideration of EV-specific issues. This taskforce is due to report in late 2021.

- The Australian Government Future Fuels Strategy for integrating EVs with the electricity grid has identified research on consumer charging behaviour and mechanisms to encourage charging outside of peak electricity demand periods as priorities (DISER, 2021).

1.3.6 Unidirectional-managed charging technologies

Electric vehicle charging can be managed by EV customers or by third parties such as utilities, charge-point operators, or aggregators. Charging can be managed through a number of different pathways including:

- Direct load control of EVSE
- Load control via vehicle telematics
- Behavioural control through pricing incentivisation

The most basic EV chargers are not communications-networked but use a direct connection to provide charge and communicate with EVs. Managed charging for EVs connected to non-networked EVSE can be implemented via vehicle telematics or user behaviour incentives that allow EV owners to manually program charging at specific times to exploit cheaper energy tariffs or solar generation.

Communications-networked or smart chargers allow direct load control by third parties such as utilities and aggregators to remotely adjust the charging settings of the EVSE based on grid needs, customer preferences, and price or demand response signals. These are increasingly converging around a communications protocol known as Open Charge Point Protocol (or OCPP) and can provide utilities or aggregators with standardised data streams to facilitate optimised charging across multiple stations or fleets of vehicles (Hurlbut *et al.,* 2020). According to AGL (2020) however, there is still some variability in OCCP implementation and interpretation across the smart charger landscape. A comprehensive overview of managed-charging from a utility perspective is provided by SEPA (2019). SEPA indicates that approximately one-third of EV charger manufacturers offer charging stations with utility control capabilities (SEPA, 2017). Smart/Networked Level 2 charging stations are currently more expensive than non-networked versions, generally by around $500-1000. However, this gap is likely to narrow as production volumes increase to service the home charging market. Other costs to consider when deploying smart EVSE systems more widely include software platform development and ongoing operational costs associated with customer and EVSE management.

After-market product companies such as GreenFlux DUO have developed devices that attach to EVSEs that can also provide an alternative pathway for managed EV charging for utilities or

aggregators (see Table 5). These systems currently support only a limited number of protocols but can work across EVSE manufacturers (Hurlbut *et al.*, 2020).

An emerging technology for EV smart charging is based on software that connects with vehicle APIs that are potentially available in some EV models. This approach connects software wirelessly or through the vehicle OBDI (on-board decoder interface) port to control basic EV functions such as switching charging on and off and to collect data on the vehicle's operation. A web portal can then be used by EV owners and third parties to set charging preferences for individual vehicles or fleets. AGL is planning to use his type of technology in its EV orchestration trials (see Trials section on p65 and in Appendix 2. EV Trials).

The big advantage of these systems is that, if implemented well in vehicles, minimal hardware investment is required for EV-grid integration on the grid side as the systems are mostly software driven from the grid perspective. However, there are many barriers. According to Chhaya (2020), strong sales-driven justifications with positive cost benefit and a predictable standardisation landscape are required before vehicle manufacturers will fully commit to the development of new in-vehicle capabilities to facilitate managed or bidirectional charging. This is a barrier to implementation because fully realising the benefits of the technical feasibility/maturity of grid-integrated EVs requires commercial viability, cooperation between utilities and OEMS, and stability in the regulatory environment. These are all largely missing in Australia and internationally.

Developers of these vehicle-integrated systems aspire to more advanced functionality in the future to completely integrate with the EV automakers' cloud services. This means that the data captured could create a detailed picture of what a vehicle is doing at all times throughout its life, including when it is charging, driving, disconnected, connected and complete, connected and not charging, connected and starting charging, connected and stopping charging, or unknown (McCarty and Grunkemeyer, 2020). A major barrier to the successful development and deployment of these systems is that they require vehicle manufacturers to cooperate and/or provide access arrangements to their vehicles' APIs and OBDI port controls. Only two vehicle manufacturers –Tesla and Hyundai – currently provide access to their APIs (AGL, 2020). Set up costs of the data platforms and privacy issues associated with the data collected are also barriers.

Examples of vehicle-integrated smart charging systems include:

- Flexcharging[1] – API-based smart charging system which uses vehicle API and the cloud platform to collect/store data and potentially control charging

- FleetCarma[2] – smart charging system that uses an attached device that connects to vehicle OBDI port and the cloud platform to manage data and smart charging

Electric vehicle charging 'orchestration' systems can be thought of as aggregation platforms that can fully control a fleet of EVs by integrating networked EVSEs, vehicle-integrated charging management, and local utility load control systems. These are currently early-stage, immature technologies being implemented primarily in pilot studies and technology trials. EPRI in the USA

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[1] https://www.flexcharging.com/

[2] https://www.fleetcarma.com/

has developed an Open Vehicle Grid Integration Platform (OVGIP) which aims to be a single interface that uses open standards to integrate an EV fleet with the full range of utility needs. These range from load management and renewables integration through to the different types of grid support. OVGIP is currently a pre-production working prototype that has been implemented in several US pilot trials and is entering a commercialisation phase (Chhaya, 2020). AGL's EV orchestration trial is aiming to test the component and platform technologies to control a fleet of up to 300 EVs (AGL, 2020).

Details of further trials of managed charging technologies that have been implemented in Australia and around the world are outlined in the Trials section (page 65). The most complex managed-charging technologies are those that also enable bidirectional charging so that energy can be discharged into a house (V2H) or grid (V2G); these are examined in more detail in the following sections.

Table 5 below was developed by AGL for its IRENA-funded orchestration trial and succinctly summarises the status of key managed and bidirectional charging technologies in international and Australian markets.

Table 5. Summary of managed charging technologies (AGL, 2020)

Technology	Status in leading international markets	Australian context
Smart charging – Infrastructure	- Relatively simple/mature technology - Cost reductions likely as volumes scale up and designs are 'right-sized' for home charging - Smart charging stations use the OCPP open communication standard; v1.5 and above provide smart charging capability. Variations in interpretation generally mean that proprietary integrations are still required. - Communications (WiFi, cellular, ethernet) can be difficult to install, unreliable, or costly for home applications. - The UK Government's EV Homecharge Scheme mandated that all EV home-charging solutions must be 'smart' from 1 July 2019.	- Largely consistent with leading international markets, although the costs/logistics to support the local market increase prices and reduce product choice. - Smart chargers are $500-$1000 more expensive than non-networked chargers which themselves are more expensive in Australia than elsewhere due to small market size and local market certification requirements. - Australian Standard 4755 requires smart chargers to have a uniquely Australian approach to load control, which, if ratified, may have significant consequences for the cost and availability of chargers.
Smart charging – Vehicle API	- These are proprietary solutions with evolving commercial arrangements. Manufacturer-specific interfaces and agreements are likely to prevail for the foreseeable future. - Vehicle manufacturers will seek to monetise connected car data, and while costs are still uncertain, they are likely to be low (after the set-up cost) for orchestration use. - The primary use case for telemetry products and services more generally is for fleet operators rather than private vehicles. - Access arrangements need to account for privacy issues, for which regulation will likely evolve with the market. - Indications are that vehicle manufacturers will integrate with third-party data marketplace operators who will play the role of the 'app store' given the requirements for data management and the various service models.	- Tesla offers an API agreement for vehicle owners but with constraints on third-party integrations and access. Smart charging trials using vehicle telemetry in Australia are using Tesla vehicles. - Most other manufacturers do not currently support APIs for access to vehicle telemetry in Australia. While this will no doubt come, timing is uncertain.

Vehicle-to-grid (V2G)	• Early-stage technology, with first generation commercial products only just beginning to emerge in limited volumes. • Make/model-specific and mostly limited to Japanese vehicles, e.g., Nissan Leaf and Mitsubishi Outlander plug-in hybrid. • OCPP v2.0 addresses V2X functionality, however, draft standard will require proprietary integrations to address large variations in interpretation. • Grid export capability will require market-specific implementations, which may increase the focus on V2H/B over V2G in the short term. • Vehicle manufacturer commitment and convergence on a V2X technology roadmap appears to be some time away.	• Test deployments in controlled environments only. • AS4777 demand management modes are a uniquely Australian requirement which will reduce product availability and increase unit costs. • Both Nissan and Mitsubishi have been enthusiastic about V2G as a unique selling proposition to solar PV owners. • The Wallbox Quasar V2G charger is currently undergoing local market certification, with supply expected in late 2021.
EV aggregation platforms	• Primary used in fleet and public charging applications • Key limitations around the end-user experience, with bespoke implementation required for third-party platforms, local energy market integration, and white labelling for brand • * Pilot-scale only deployments for vehicle API integrations (e.g., ev.energy/UK, Flexcharging/US) and for V2G applications (e.g., Ovo/UK)	• Very limited options and low feature maturity, with commercial models still evolving. Solution providers locally include Chargefox, Evie Networks and EVSE • Chargefox built basic smart charging capability into its platform for AGL's NSW DR program in 2018 and is extending this for AGL's larger EV orchestration trial. Origin is using GreenFlux (NL) for a smart charging trial. • ev.energi (UK) and Flexcharging (US) have demonstrated vehicle API capability in Australia

Chhaya (2020) has outlined five insights related to challenges with managed charging and intelligent EV-grid integration which provide a useful summary –

- **Insight 1**: 'Many to Many Problem'
    - 3000 utilities, 20 OEMs - too many permutations and combinations
    - Even if the list is whittled down to 100 by 10, it is still too big
    - EV penetration is not uniform across the country; the need to manage charging is not universally felt; there is a lack of critical mass for standards adoption on both sides

- **Insight 2**: Are we over-thinking this? What are the *real* requirements?

    - Goal is to reduce charging during times of congestion

    - Delay charging to times when renewable energy is available

    - Need timed charging to soak up excess renewables

- **Insight 3**: Utilities want uniformity to address the entire EV-installed base wherever they are plugged in, at the lowest possible total cost and without the risk of stranded assets.

- **Insight 4**: Utilities could use actual operational data from EVs for distribution planning and operations

- **Insight 5**: The OEMs want to deliver the energy and data services that utilities need while maintaining implementation flexibility to utilise lowest-cost options that are reliable and cybersecure, preserving PII protections for the shared customer.

1.3.7 Bidirectional charging technologies (V2G/V2H)

The average Australian passenger vehicle travels around 11,000km per year, which equates to an average daily charging requirement of the order of 7kWh (Graham and Havas, 2020). With assumed EV battery sizes in the range 30-50kWh, this represents daily charge and discharge for driving in the range of 15-25%, proportional to battery capacity. If the energy were to be stored and sit largely unused in the battery, this could be considered a significant under-utilisation of the capital expense (and associated resource usage and environmental footprint) of an EV battery. As EV batteries have a finite shelf life, it makes sense to explore opportunities to get the most benefit and value out of them by using the 75% excess energy that is surplus to travel requirements while they are still usable and inside a working vehicle.

Vehicle-to-grid (V2G) and Vehicle-to-house (V2H) systems have the ability to both charge and discharge an EV and can therefore potentially capture some of the benefits and value of excess energy in EV batteries via a number of different 'use cases' such as ToU arbitrage or provision of grid services. Although definitions vary, the following points are sufficiently general to be useful here:

- V2H technologies discharge energy directly into households. They generally work behind the meter at residential premises and can operate without need for real-time network interaction (or with only minimal interaction) and in the same way that a stationary household battery does. V2H operational parameters will be primarily determined by customer load profile and tariffs and may be used for customer bill management, for example, by exploiting tariff differentials and maximising self-consumption of PV. The CSIRO/Ausnet Services V2H trial is a good V2H example (see Trials)

- V2G technologies discharge energy directly to the grid and are more likely to be centrally and actively controlled by a utility or aggregator and to provide grid services like FCAS, voltage control, or demand response. V2G requires an active communications connection between utility/aggregator/vehicles/charge-points at all times when vehicles are connected, which requires cooperation across the various stakeholders and charging technologies. V2G hardware can be built into either an EVSE or onboard an EV. The ANU REVS trial providing FCAS is a good example of V2G (see Trials section (page 65).

In terms of residential energy usage, the average Australian household uses around 16 kWh/day, which equates to somewhere between 30-50% of the capacity of a typical EV battery. As such there is ample room for EVs to substantially contribute toward required energy needs of residential houses through V2H systems. According to Graham and Havas (2020), it is generally expected that as solar generation capacity increases in the long term, the lowest-priced period for drawing electricity from the grid will be around midday. The authors indicate that workplace charging – and other daytime charging of fleets of EVs with V2H capability – could be highly beneficial when functioning as a 'solar sponge'. This could time-shift solar generation directly to households at peak time in the early evenings and then top-up again overnight if needed when demand is low.

Current significant barriers to V2G/V2H implementation include battery degradation issues, maturity of technology, regulatory requirements, and compatibility of EVs and EVSE with bidirectional charging. Uncertain costs include hardware, communications, back-end systems, and battery degradation. In certain circumstances, managed and bidirectional charging can impact negatively on battery life. Although V2G/V2H can potentially provide flexibility for smart EV-grid integration, it may not be attractive to OEMs and consumers if degradation occurs. Conversely, charging can also be managed in a way that maximises battery life but may reduce flexibility for the provision of grid services. The reasons why OEMs provide such a large excess of battery capacity is to address range anxiety and to ensure that battery warranties can be upheld considering the batteries' ready degradation under the wide range of possible usage conditions even without V2G/V2H. A battery that is driven hard and charged often with fast-charging will degrade much more rapidly than a lightly driven, trickle-charged battery. The up-shot is that OEMs and customers may not be willing to allow access to spare battery capacity for grid or customer benefit unless the value can be captured and warranty preserved or waived.

Bidirectional charging can be implemented via external charge points or in-vehicle chargers. External bidirectional chargers are a fairly immature technology with low volume production and currently around $10,000 more expensive than a basic charger (AGL, 2020). A UK-based study has estimated that this cost differential may be reduced to around $1200-2400 over the next decade (Element Energy, 2019). In many use cases, uncertainty also remains about how any derived benefits will flow to customers or networks who invest in the technology and whether the cost-benefit ratio is worthwhile. If the total price premium for V2G/V2H is in the order of a few thousand dollars, then it seems promising that this could be recovered over time through various value streams. The potential value of V2G/V2H services is explored in more detail in the following section.

Currently, Australia has only a small number of EVs and charging infrastructures that are capable of feeding energy back into the grid. The second-generation model Nissan Leaf and the Mitsubishi Outlander PHEV have V2G/V2H capability. Renault Zoe also has V2G capability but is no longer available in Australia (Jones *et al.,* 2021). Several other car companies are looking to implement V2G, including Honda and BMW (De Bruijn, 2020). Although technically feasible, there are many barriers for OEMs to overcome before in-vehicle V2G platforms are ubiquiToUs and widespread, including commercial viability, lack of agreed standards, and lack of cooperation between/across OEMs/utilities (Chhaya, 2020). In 2022 it is expected that the Wallbox Quasar, a 7.4kW bidirectional external chargepoint for residential settings (Wallbox Smart Charging, 2021) will be available pending the resolution of Australian regulatory

compliance issues (AS 4777). EV-NRG[3] is also looking to bring a UK-developed V2G charger into the Australian Market in 2021 (Indra, 2021.

According to Chhaya (2020), strong, sales-driven justifications with a positive cost-benefit ratio and a predictable standardisation landscape is required before vehicle manufacturers will fully buy into the development of new in-vehicle capabilities to facilitate managed and bidirectional charging. This is a barrier to implementation because even when we have technical feasibility/maturity for grid-integrated EVs, the full realisation of the benefits requires commercial viability, cooperation between utilities and OEMS, and stability in the regulatory environment; currently, these are all largely missing both in Australia and internationally.

Another barrier for V2G/V2H is the charging standards as outlined in Section 2.4.1. Currently the CHAdeMO vehicle connector standard offers the only V2G in Australia, but it is gradually being phased out in Europe and North America. A future version CCS Combo 2 is planned to accommodate V2G support.

One of the first Australian V2H trials was undertaken by CSIRO and AusNet Services in 2013/14 (Ausnet Services, 2014). The trials were aimed at demonstrating the ability of a V2H system to reduce the peak load drawn from the grid at an individual residence. The trials demonstrated that even with a small battery vehicle (12kW) and available discharge power (1.1 kW), a significant reduction of household peak demand could be achieved whilst still meeting the daily EV commuting needs.

REVS and AGL trials are both looking to trial emerging bidirectional charging technologies (see Trials); REVS is aiming to provide FCAS through V2G, and AGL is looking at trialling V2H technology. AEMO is currently conducting a consultation on the Ancillary Service Specification relating to Contingency FCAS markets (AEMO, 2021a) and exploring the potential to simplify access to this potential revenue stream for EVs.

Key barriers to bidirectional charging

- Immature EV orchestration or grid integration technological developments like V2G/V2H. These technologies are still emerging, generally not available off the shelf, not well standardised across vehicles, and in some cases curtailed in EVs for third party access (or not implemented) so that potential value streams from vehicles remain under control by EV manufacturers.
- Grid connection hurdles: Bidirectional installations require extra grid connection assessment due to being a generation source – this increases the complexity and time to get approvals for connection.
- Consumer unfamiliarity with V2G: EV owners and fleet operators are currently unaware of V2G or aggregation business models.
- Lack of consensus on appropriate standards in vehicles/chargers/utilities
- Lack of proven business models
- Privacy issues in relation to data collection and management
- Immature technology; limited product availability
- Costs of hardware, operations, platforms, coordination, and battery degradation
- Risk-averse industries

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[3] https://ev-nrg.com/

- Access to ancillary services markets for value stacking
- Fear of possible negative grid impacts, overload, congestion, and power quality impacts if all systems synchronise poorly to exacerbate peaks.

1.3.8 Value of managed charging and V2G/V2H services

Given the significant cost barriers to different types and scales of V2G/V2H implementations, it is important to quantify potential value streams so these can be weighed against the costs as outlined in the previous section (costs include hardware, software systems development/operation/ maintenance, and battery degradation).

The most comprehensive analysis of the costs and benefits of a range of bidirectional charging 'use cases' was commissioned by the California Public Utilities Commission in the USA and undertaken by a consortium of parties in their Vehicle-Grid Integration (VGI) Working Group. Their recently completed study (California Public Utilities Commission, 2020) asked –

- What VGI use cases can provide value now, and how can that value be captured?
- What policies need to be changed or adopted to allow additional use cases to be deployed in the future?
- How does the value of VGI use cases compare to other storage or DER?

The VGI Working Group developed a range of cost-benefit analysis methods and then applied these to the 240 potential use cases. It concluded that the potential market for VGI solutions is diverse and interwoven across a broad swathe of the transportation and power sectors. Importantly, it found that there are many potential VGI use cases that can provide a positive return on investment and value for money right now. Some of the highest potential value use cases related to applications in:

- Customer bill management via arbitrage: Storing cheap or site-generated energy and using this when prices are high
- Avoiding or deferring investment in upgrading the power distribution grid
- Home and building backup power and resilience
- Daytime charging to support balancing and storing renewable energy
- Indirect (passive) control approaches, such as time-varying retail rates and responding to informational signals of grid conditions (i.e., carbon signals or real-time wholesale energy prices) that do not require specific customer behavioural responses

Figure 16 shows the range of potential annual revenues that can be generated for EV owners based on 240 different cases studied. On the second vertical axis it also indicates the number of EVs that could participate in these applications in 2022. This analysis shows that the derivable value from a grid-integrated EV ranges up to $1140 AUD per annum.

In Australia, the REVS project (Jones *et al.,* 2021) has also made estimates of the potential value that can be derived from EV provided grid services. This study took the simple approach of estimating maximum potential revenue based on an extreme upper bound value, where the EV is used effectively as a stationary battery and continuously plugged in and available to the grid and not used for driving. The project's estimates are therefore significantly larger and, as shown in Figure 17, are in the range of $2500 to $5000 per year.

AGL has also made some estimates of value that could be created from V2G in Australia as part of its due diligence in designing its EV orchestration trials. AGL's estimates are that between

$300 – $600 per charger per year of total value could be created through V2G (AGL, 2020). This means that, at an individual charger level, while the technology is cost-prohibitive today, the most optimistic 2030 bidirectional charger price forecast shows potential for a 2-year payback (Element Energy, 2019).

A simple calculation based on ToU arbitrage based on tariff differential of $0.15 per kWh and EV discharging for an average of 2 hours per day at 3.6 kWh works out to around $1 per day of revenue or around $350 per year.
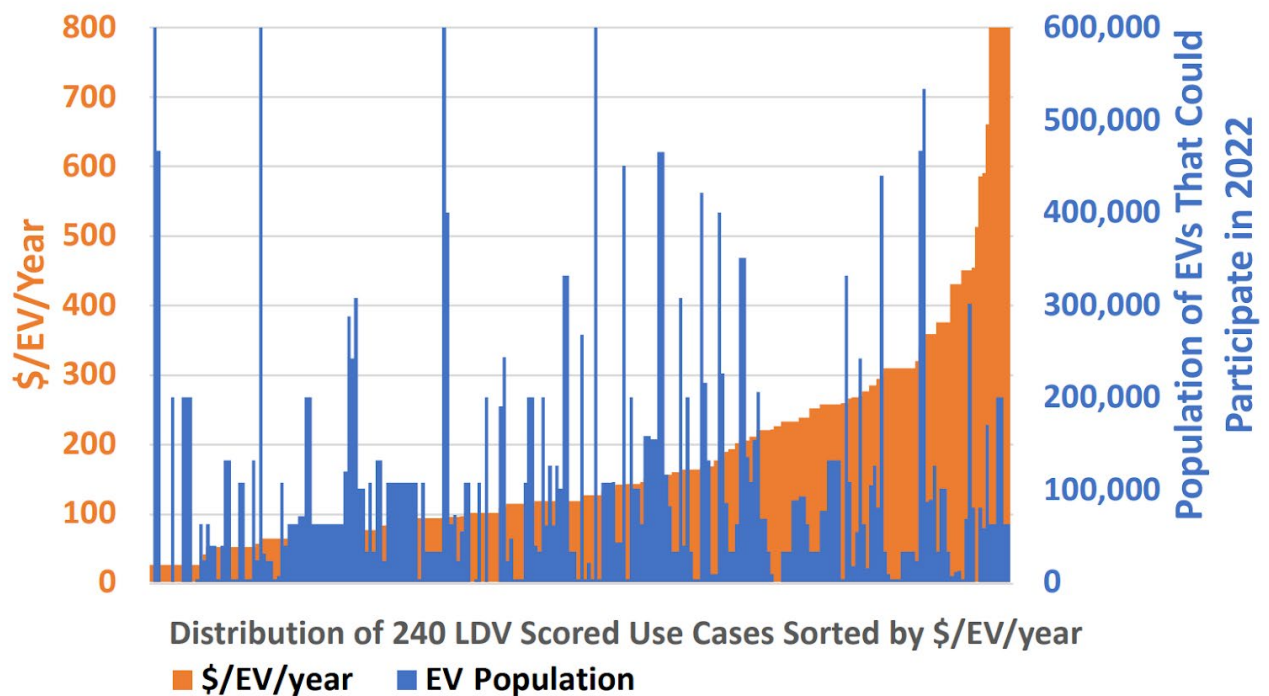
Figure 16. Results from an analysis of 240 different vehicle grid integration case study examples for California (California Public Utilities Commission, 2020).

	2010	2019
■ Regulation Lower	$922.91	$1,694.02
■ Regulation raise	$1,479.65	$2,009.99
■ Contingency Lower	$59.56	$45.13
■ Contingency raise	$747.46	$915.45
■ Energy	$279.71	$973.63
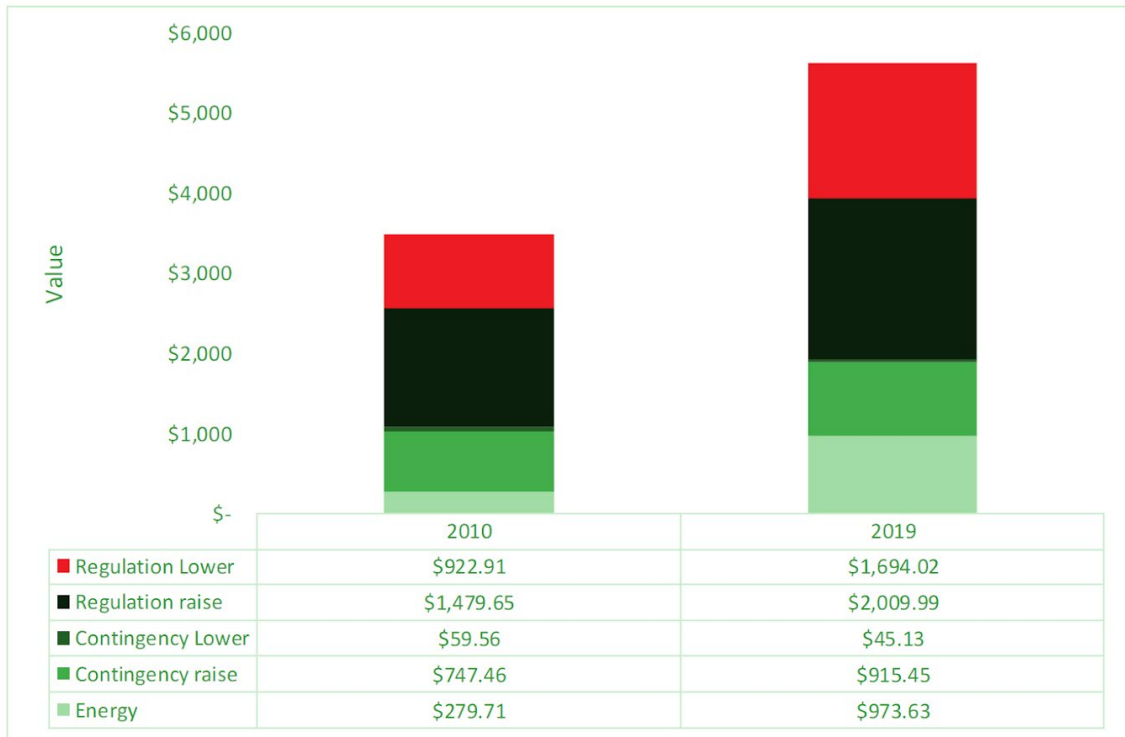
Figure 17. Approximate EV charger revenue for New South Wales (Jones et al., 2021).

1.3.9 Broad trends at the nexus of EVs, transport futures, and grid integration

In the near-term future (up to 2030), the increasing availability of EVs with lower prices and increasing battery sizes, and the increasing amount of renewable generation coming online, will greatly increase the opportunities for using managed and bidirectional charging to provide a flexible resource to help smooth the transition of the energy system to support large-scale EV uptake with high penetrations of renewable energy.

Trends in the medium term (2030) that will contribute to this include:

- The number of EVs will increase rapidly

- Battery packs will be bigger, increasing from 20-30 kWh currently to 40-60 kWh (IRENA, 2019)

- Cars, charging stations, and home charging will have increasing functionality for smart charging and discharging

- Increasing prevalence and consumer acceptance of business models incorporating aggregators and value stacking grid services and arbitrage

- Increasing opportunities for EV drivers to charge on streets, carparks and workplaces

- Increasing integration of EV charging with site/building energy/demand management

- Fast charging will remain limited as drivers will use it mainly for long-distance trips and for necessary top-ups given that enough range is available and as long as charging at home remains cheaper.

- Fast charging capacity during the day, however, will be increasingly aligned with grid needs in areas with high solar production during the day.

Trends in the longer term (2050):

- The rise of new mobility business models and autonomous vehicles may lead to reduced individual vehicle ownership and increased fleet ownership and management.

- An increase in the use of ride sharing or other emergent mobility services could lead to an increased amount of total travel, especially if commuters shift away from public transport

- It is likely that new mobility business models would optimise the utilisation of their main assets – the vehicles – such that they are used as much as possible to maximise returns (similar to aircraft fleets). This will reduce the amount of time that they are idle or connected to the grid and reduce the flexibility available for value stacking grid services.

- Advanced mobility business models could therefore, in the long term, result in a reduced number of better utilised EVs on the road. These would be potentially more concentrated in space when they are connected to the grid, which would concentrate grid impacts compared to while EV-grid connections are more distributed in alignment with individual EV ownership.

- Concentrated zones of grid-connected EVs will be charged according to fleet goals, perhaps in a model closer to electric buses (i.e., in depots). The future configuration and operation of the grid and transport networks will therefore need to be considered in combination.

1.3.10 Demonstration, pilots, and trials of EV-grid integration

Overview

This section provides a snapshot of gaps and opportunities related to the trials, pilots and demonstrations that are looking to progress optimised EV-grid integration from Australia and internationally. A summary overview of some example trials and links to the relevant trial data and information are provided in Appendix 2. The examples of completed and current trials involve:

- Managed charging

- Bidirectional charging/discharging

- ToU or dynamic pricing-based charging incentives

- Data made available for research where possible

Recently completed and current trials cover a wide spectrum of approaches to advancing optimal EV-grid integration. In summary, the example trials reviewed have sought to:

- Test and gather data on new technologies and business models for managed and bidirectional charging

- Understand EV users' behaviour and interaction with incentives and new technologies

- Gather real-world data on EV impacts on electricity grids

Key observations from these examples are as follows:

- Extensive trials have been undertaken or are underway in more mature EV markets in the US, Asia, and Europe than locally, but Australia is now catching up, with several current IRENA-funded trials.

- Trials are expensive to run, especially those involving new technologies. Several million dollars of funding are required to run even a small pilot trial.

- The pace of technological change is also potentially challenging. Trials and pilots of new technologies are often outdated by the time they are completed. An example is The EV Project, which was a large EV pilot program in the US that deployed 8000+ vehicles. As these were mostly convenience-charged, with very few trialled under managed charging technologies, results are not as useful today as we know quite well what convenience charging looks like and can reasonably project its (largely negative) impacts under wide-scale uptake. Trials of managed charging technologies are needed to see how users respond, but these will potentially be outdated if bidirectional charging becomes a value creation prospect for owners. Related technologies may also eventually be superseded by direct EV 'orchestration' control of EV fleets through in-vehicle control technologies.

Gaps

- Successful, optimised EV orchestration requires an understanding of the current EV state as well as of future travel requirements of the EV user. This is recognised in the technical literature and generally studied using modelling with a range of assumptions. Trials of engaged EV users offer an opportunity to directly collect real world user travel requirements and map these to individual behavioural responses to managed charging technologies and incentives. If these data were collected in parallel with the EV/charging/grid data, we could better understand how technologies and incentives are impacted by different user contexts. It appears that future travel requirements are not widely collected in trials and therefore this analysis is lacking.

- In the Australian context only a very small number of trials is targeting V2H technologies and workplace charging. This is a gap considering that the largest time window of vehicle plug-in for potential grid interactivity is at residential premises, followed by workplaces.

Opportunities

Given the very large expense of running trials and the breadth of existing and past initiatives, RACE to 2030 may be in a good position to –

- Engage with current trials with the aim of adding value to downstream research based on the data collected. Given the publicly funded aspects of these programs (i.e., IRENA funding), these should be freely available.

- Undertake a study that includes a detailed meta-analysis of all international EV trials and available EV datasets to identify gaps that are aligned to specific local industry needs. This could be used to inform future trial designs undertaken through RACE to 2030 or elsewhere.

2. EV Grid Impact Assessments, Policy, regulatory framework, standardisation

2.1 Introduction

This section of the report provides a literature review on barriers[4] and opportunities of the large-scale adoption and integration of electric vehicles within power grids, focusing on the following topics:

- Integration of electric vehicles in power grids
- Policy regulatory frameworks
- Standards and grid codes

2.2 Review of Electric Vehicle Grid Integration Impact

The barriers, opportunities, mitigation solutions and practical case studies on the large-scale integration of electric vehicles to power grids are analysed under four major areas: 1) Barriers and opportunities to electric vehicle charging on networks, 2) System operation and control barriers and opportunities, 3) Barriers and opportunities to vehicle to grid (V2G) operation, and 4) Barriers and opportunities to EV orchestration with distributed energy resources (DERs).

2.2.1 Barriers and opportunities to electric vehicle charging on networks

The rapid adoption of EVs, combined with localised clustering of the vehicles, would primarily affect low-voltage distribution networks. High EV uptake, network clustering, battery size, charging behaviour, and choice around the time of charging are some of the major causes of electrical grid impact. Based on the specific charging technology (e.g., trickle (Level 1), fast (Level 2) or rapid (Level 3)) the connection of a single EV is equivalent to between one and twenty new homes (depending on the EV charging level) added to the electricity network (Toner and Heinen, 2018). Collectively, the relatively high power requirements of EV charging will fundamentally change electricity consumption patterns, and if the EVs are not well controlled, it will place significant strain on the power grid (Shariff *et al.*, 2019). The following subsections provide a review of identified barriers to EV grid integration from a network point of view, with proposed mitigation strategies to alleviate network impact and opportunities for further research.

a) Violation of network voltage limits stipulated in grid codes

The growing number of residential EV chargers may trigger several challenges for the power distribution networks. Generally, power system voltages are regulated within specified limits stipulated in grid-code standards by controlling the reactive power (i.e., injecting reactive power to increase the voltage, and absorbing reactive power to decrease the voltage). Expanding EV penetration may result in sustained under-voltage conditions, violation of under-voltage limits, and voltage unbalance, which would deteriorate the service voltage quality in residential low voltage (LV) feeders (Dubey and Santoso, 2015). For proper operation of the power system, adequate voltage control mechanisms are essential. In addition to these EV-related issues, voltage control in power grids has become more challenging over recent years as the increasing

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[4] Detailed barrier analysis is given in Appendix 1.

penetration of DER export power is straining networks that are already operating near the upper limit of their allowable voltage range (Habib *et al.*, 2018).

Practical case studies of the problem

According to an analysis conducted by Masoum and colleagues, EV charging has a role in voltage deviations and power losses. This study analysed four EV penetration levels and three different charging rosters and indicated that the node voltage dropped below the regulatory limit, leading to increased losses for all of the uncoordinated charging cases (Masoum *et al.*, 2011).

The Californian Electric Power Research Institute (EPRI) has examined the impact of EV charging on distribution network voltages. This research used a low voltage network consisting of 74 houses from a suburb of south Dublin, Ireland. The pilot study assumed that 50% of houses in the network had EVs that would charge at points throughout the study. Test results depicted how the uncoordinated charging of the EVs caused the feeder voltage profile to violate network standards (EPRI, 2012).

Mitigation Strategies/Solutions

EVs equipped with Vehicle to Grid (V2G) controls could offer voltage support and power factor correction by controlling the reactive power without substantial impact on the EV battery life (Dubey and Santoso, 2015). Reactive power can be injected into the grid from a V2G EV charger by controlling the AC-DC converter and the DC-link capacitor without affecting the current drawn from the EV battery. This also means that, in the case of DC chargers where the converter is integrated within the charger instead of the vehicle, the vehicle may not be required to be plugged-in for the charger to provide reactive power support. This makes the installation of V2G DC chargers extremely suitable for reactive power control. V2G fast chargers may also be able to provide reactive power support. This can assist with mitigating voltage fluctuations without fully discharging the vehicle's battery. The effectiveness of reactive power support from EVs for LV feeder voltage management and improvement of power factor have been reported by many studies (Dubey and Santoso, 2015). The barriers and opportunities regarding V2G will be discussed in detail in Section 2.2.3.
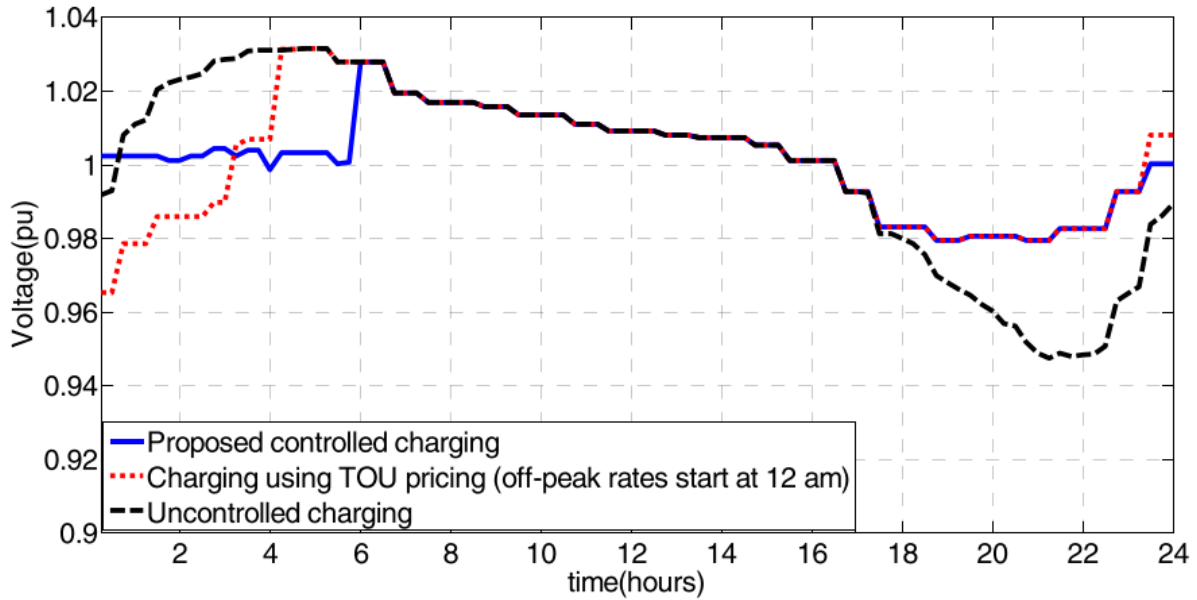
Figure 18.Voltage profile at the EV load location with controlled and uncontrolled charging (Dubey and Santoso, 2015).

Practical case studies of the mitigation strategies

Despite several mitigation schemes – such as indirect control using time of use (ToU) tariffs and direct control using smart charging algorithms – that have been proposed to improve network voltage profiles, Anamika Dubey et al. have instead proposed a controlled charging algorithm to improve the voltage quality at the EV load locations to avoid customer inconvenience. The proposed method has significantly decreased the impacts of EV load charging on system peak-load demand and feeder voltages by optimally shifting the EV load demand to off-peak hours. Although this scheme was designed to mitigate voltage variability issues at the secondary customer location, the algorithm also delivered utility benefits by minimising the substation peak-load demand and using the distribution grid more efficiently.

In another charging trial, a 3.7kW three-phase EV charger was used with a 14.5kWh battery and a 6kW three-phase PV unit. The trial demonstrated that the proposed coordinated EV charging strategy could reduce voltage rise by approximately 2.65% at the point of common coupling (PCC), regulating the voltage within the defined limits in grid codes (Marra *et al.*, 2013).

b) *Violation of capacity limits of network assets (e.g., transformers), protection malfunction, and network congestion*

In the majority of EV customer homes, the EV charger is the largest single load and can potentially raise the peak demand, and hence the congestion on the network, considerably (see Figure 19). Single EV households have the potential to increase their electricity capacity needs between 100% for very slow trickle charging and 2000% for rapid charging (Toner and Heinen, 2018). This essentially equates to adding between one and twenty additional 'households' (depending on the EV charger type) to the power distribution network at peak load conditions (Toner and Heinen, 2018), significantly overloading the distribution network assets under such operating conditions.
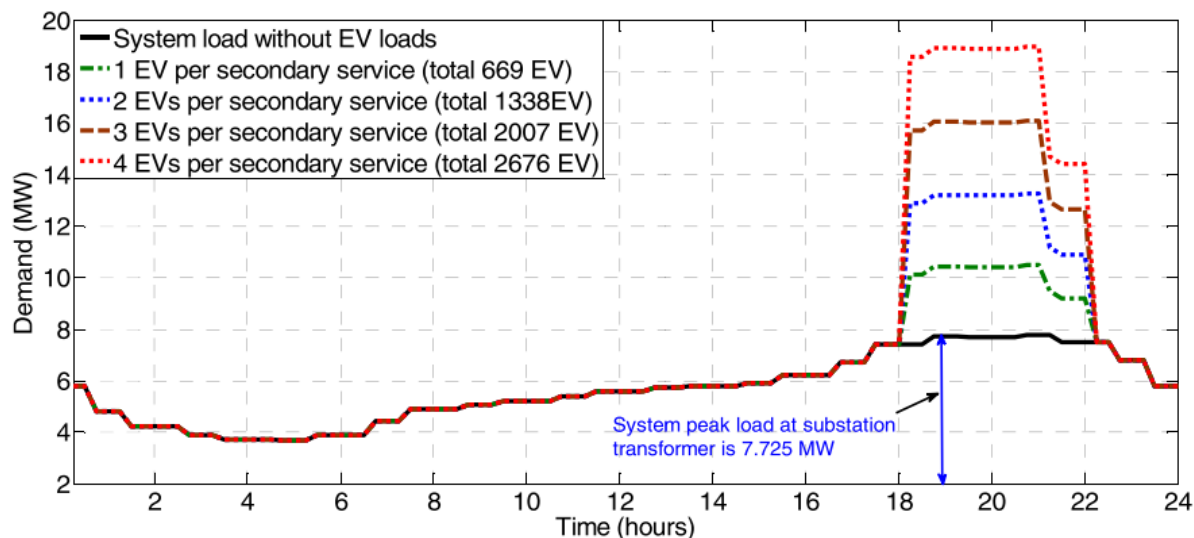
Figure 19.Hourly load demand profile, with and without EV loads, measured at the substation (Dubey and Santoso, 2015)

There are other challenges that need to be addressed along the way. Some, like network congestion, are common to other distributed energy resources, and network congestion may be intensified by EVs and V2G (Vassileva and Campillo, 2017). Large-scale deployment of EVs places great stress on distribution transformers and conductors. If charging infrastructure is not designed appropriately, then the extensive adoption of EVs over the distribution circuit can greatly increase the substation load demand. Consequently, the generation capacity of the power grid may need to be increased to cater for the increased energy demand of EVs (Morrissey, Weldon and O'Mahony, 2016). The non-linear characteristics of EV chargers may cause harmonic distortions (depending on the charger topology and network parameters), which further create stress on LV fuses, cables, and power transformers (Habib *et al.*, 2018). Increased EV load demand may overload substations and service transformers, thus deteriorating the transformers' life.

Mitigation strategies/solutions

Smart charging and V2G can avoid local network congestion caused by EVs and defer the network investment (Jones *et al.*, 2021). Smart-charging strategies could enable charging during low demand periods, and V2G strategies could provide additional services to manage the network congestion.

Practical case studies

> *"The 'My Electric Avenue' project in the UK is designed to investigate the influence of clusters of EV chargers on network congestion. This project involved 200 EVs in the southern UK, 100 of which were in single street clusters of around ten. This project showed that unmanaged EV charging has the potential to double localised peak demand. Importantly, this trial used older generation Nissan Leaf vehicles with relatively small 3.3kW inbuilt chargers. Modern EVs commonly charge at double this rate. Even with 3.3kW chargers, this report revealed that congestion begins at around 50% EV penetration within a local network. It predicted that if*

charging were unmanaged, 32% of LV feeders across Britain would need reinforcement by 2050.

The project also indicated that unmanaged charging could cause 32% of distribution transformers in the UK to require replacement when 40-70% of customers have EVs. This demonstrated that managing charging could avoid network reinforcement" (Jones *et al.*, 2021).

c) Network augmentation costs and reluctance on network upgrades

The additional load from the EV charging could result in the overloading of the local distribution networks relative the extent to which these chargers are clustered on the same circuit. This in turn will require network reinforcement to avoid overburdening of assets. Even at low EV penetration (10-20% on a network feeder or neighbourhood), low voltage capacity constraints can occur if charging occurs during peak time and/or uses faster charging options. If 7kW chargers are deployed, low voltage network expansion costs can range from U$100 million (AUD 130 million) for 10% to U$530 million (AUD 690 million) for 40% penetration (Toner and Heinen, 2018).

Peak demand is one of the key drivers for network investment. Without controlled charging, large-scale EV deployment could decrease supply adequacy and will therefore necessitate the construction of additional power plants (Mark Toner and Steve Heinen, 2018). It is clear that without any planning or preparation, high electric vehicle uptake could put significant stress on the electric power system and increase the maintenance costs. However, with proper planning transportation electrification can result in the more efficient and economic operation of the grid, provide ancillary services, lower electricity prices for ratepayers, and facilitate greater integration of renewable energy resources (Hall and Lutsey, 2017). If not managed properly, EVs will cause challenges that may lead to grid over-investment in order to cope with the extreme operating conditions (Knezović *et al.*, 2017).

Practical case studies of the problem

In the United Kingdom the 'My Electric Avenue' project estimated that with 40–70% of cars electrified and using uncontrolled charging, 32% of distribution circuits would require network upgrades (EA Technology, 2016).

Mitigation Strategies / Solutions

Adaptation of the distribution network to effectively support the growing EV penetration has become an important challenge for distribution network service providers (DNSPs). A novel dual stage optimisation framework proposed by Zeng et al. (2017) can help DNSPs to better assess the impacts of EVs on distribution networks and also facilitate allocating their capital in planning decisions more effectively to support sustainable integration of EVs to power grids (Zeng *et al.*, 2017). A significant reduction can be realized in both investment and operation costs if the EV users incorporate a coordinated charging scheme instead of an uncontrolled mode (Zeng *et al.*, 2017). With proper planning, electric vehicles would provide benefits to the DNSPs that outweigh the network augmentation costs (Hall and Lutsey, 2017).

The DNSP network augmentation costs could be reduced by V2G via three main ways: 1) by reducing retail energy costs, 2) generating income, and 3) placing downward pressure on wholesale prices (Hall and Lutsey, 2017). V2G-equipped EV chargers can provide services such as frequency control and regulation and contingency services, and these services are based on rate-of-change of frequency, frequency error and so on (Sharma and Sood, 2021).

Lopes et al. concluded that large-scale EV adoption is possible without major grid reinforcement with advanced centralised control strategies. Smart charging and V2G can assist to increase renewable power penetration in networks (avoid potential curtailment) and reduce peak demand. This can also reduce the EV charging cost (Lopes, Soares and Almeida, 2009). The 'Electric Nation' project in the UK showed that EV charging is flexible and can be shifted to avoid network peaks (Mark Toner and Steve Heinen, 2018).

Practical case studies of the mitigation strategies

Electric Vehicles have the potential to reduce network prices if managed appropriately. A recent study conducted by EvEnergi on the South Australian network stated that, "*If managed correctly, EVs could potentially improve network asset utilisation.*" (Sharma and Sood, 2021).

Fernandez et al. showed that it is possible to avoid up to 60–70% of the required incremental investment with smart charging; smart charging makes it possible to attain the highest EV penetration level without violating the network technical limits (Pieltain Fernández *et al.*, 2011).

d) *Increase in network power losses and operating costs*

Electricity distribution feeders are resistive, hence when EVs are charging the additional power is transmitted through these cables, giving rise to higher ohmic losses. In particular, the resistance is relatively large in the power distribution grid, hence additional EV charging demand will enforce an additional burden and may adversely affect the performances of distribution grid, for example by increasing energy losses or voltage deviations, deteriorating the reliability of supply (Zeng *et al.*, 2017).
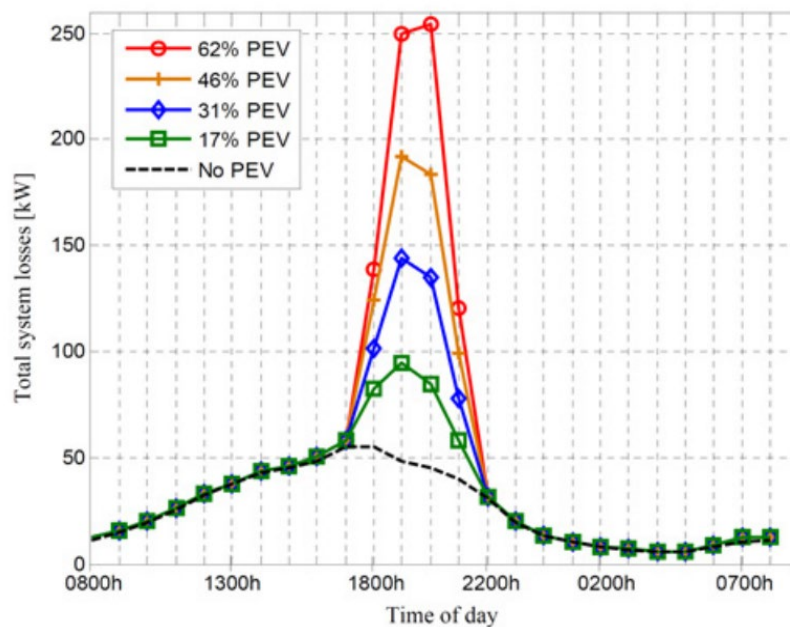

Figure 20. Total system power losses for different PEV penetration levels under random uncoordinated EV charging (Masoum *et al.*, 2011)

A large amount of power should be transmitted from power plants to cater to the EV charging demand when EV penetration is significant. The power network components (e.g., transformers

and conductors) may face overloading as the distribution components are not designed to cater the additional EV charging demand in conventional grids (Jones *et al.*, 2021). The bulk-charging scenario of EVs may further exacerbate this issue, placing distribution transformers and conductors at greater risk.

Practical case studies of the problem

Akhavan Rezai et al. examined the conductor loading for peak charging hours of EVs. The results showed that for slow and rapid charging conditions the cable can safely handle 25% and 15% penetration levels of EVs, respectively. The study concluded that the distribution networks cannot easily cater for massive integration of EVs (Rezai *et al.*, 2012).

A trial by Xcel Energy in Colorado concluded that at electric vehicle market penetration of 5%, up to 4% of distribution transformers could be overloaded if all electric vehicles are charged during peak times (Hall and Lutsey, 2017). Depending on the charging strategies, up to 15% of the total actual distribution network costs would need to be invested, and when 60% of the total vehicles are EVs, and energy losses could also increase up to 40% in off-peak hours (Yilmaz and Krein, 2013a).

Mitigation Strategies and Practical Case Studies of the mitigation strategies

Several research studies have pointed out that random charging scenarios with Level 2 charging condition and substantial EV penetration could severely impact distribution network components, especially power cables and power transformers. Since EVs are adding an additional load to a power network, the following factors should be carefully considered when planning future power networks for EV adoption (Dubey and Santoso, 2015; Habib *et al.*, 2018): 1) appropriate selection of power transformers, 2) various system configurations, 3) ratings of various components, 4) component loading scenarios, 5) various levels of EV penetration, 6) strategies of EV charging, 7) proper load scheduling, 8) smart metering and ToU plans.

Clement-Nyns and colleagues proposed an algorithm to minimise voltage deviation and reduce power losses (Clement-Nyns, Haesen and Driesen, 2011). The effectiveness of the proposed method was validated on a modified IEEE test system with 30% EV penetration. The authors showed that the proposed method can regulate the node voltages almost as if no EV loads are present. Of additional benefit was that the line current and peak load demand was reduced significantly compared to the uncoordinated charging (Dubey and Santoso, 2015).

Several technical studies have analysed the impact of EVs on system losses. Pillai and Bak-Jensen investigated the charging impact of EVs on the Danish distribution network. The outcome of the study showed that a penetration level of up to 50% of uncontrolled charging could increase the system losses by 40%, whereas coordinated charging could reduce the grid losses to 10% in comparison to a base case with no EV integration (Dubey and Santoso, 2015).

e) *Violation of network power quality limits*

Power quality is a broad term that is used to describe undesirable conditions affecting the quality of electricity supply systems. It can be defined as the deviation of the voltage and current waveform from the pure sinusoidal waveform. Power quality issues could be categorised as voltage and current unbalance, short- and long-term voltage sag and swell, poor power factor, voltage and current harmonics, and flicker. Poor power quality can reduce the life span of equipment and grid reliability. In recent years power quality problems have increased particularly due to DERs such as rooftop solar, household batteries, and EVs, which employ

power electronic converters for grid connection (Yilmaz and Krein, 2013). These issues have been further exacerbated by the growing use of non-linear loads (Yilmaz and Krein, 2013a).

Using improperly designed power electronics-based charging devices for EV charging may give rise to power quality problems in distribution networks caused by surges in the network when equipment is switched on or off. Harmonic distortion plays a major role in derating distribution components. Therefore the massive integration of EVs can affect the supply quality of the power network (Habib *et al.*, 2018).

The rise in EV penetration introduces a significant impact on power quality, which can generate undesirable effects on the power system. This could impact the peak load as well as the peak-load hours, voltage fluctuations, phase unbalance, harmonics, and system stability, thus degrading the power quality and reliability of the power system. EV chargers are power electronic converters that have non-linear characteristics. These chargers increase the voltage unbalance and create voltage and current harmonics (Hall and Lutsey, 2017). When demand exceeds the network's capacity, it has several impacts including overloading network elements and causing voltage sags or swells (Hall and Lutsey, 2017).

Mitigation strategies and practical case studies

Smart charging and V2G could improve the power quality by controlling voltage and power factor. Traditionally utility companies have utilised devices such as voltage regulators, capacitor banks, and transformers to improve power quality. Smart charging of EVs and the V2G are some alternatives to alleviate these power quality issues as they can improve power quality by effectively controlling voltage and power factor.

> "*Average personal vehicles in the U.S. travel on the road only 4–5% of the time, sitting in home garages or parking lots the rest of the day. In many cases, these vehicles can support V2G capabilities.*" (Yilmaz and Krein, 2013a)

The study presented by Anamika Dubey et.al has shown that EVs could only improve the power quality of the network when they are simultaneously connected to the power grid, which is the case for an airport or a shopping centre parking spaces with EV chargers (Dubey and Santoso, 2015). Other cases analysed are not candidates for V2G services because they do not connect a sufficient number of vehicles at the same time. In those cases it is simply not convenient to install bidirectional charging stations with sophisticated communication systems.

In order to avoid the peak demand and reduce upgrade expenses necessary for the high penetration of EVs, utilities can passively promote grid-friendly charging behaviour by adjusting the electricity rate structures while avoiding pricing schemes that penalise electric vehicle owners. Many utilities have found that ToU rates offer a simple and effective solution for mitigating these power quality issues (Hall and Lutsey, 2017). Moreover, if appropriately designed EV chargers with harmonic suppression capability are deployed in power networks the power quality issues could be mitigated.

Opportunities for further research from a network perspective –

- Coordinated smart charging and discharging integrated with smart metering can optimise time and power demand and reduce daily electricity costs, voltage deviations, line currents, and transformer load surges. It can also flatten the voltage profile of a distribution feeder. Incremental investments and high energy losses can be avoided, and wastage of renewable energy (due to curtailment during peak-hours) and network

congestion could be also prevented (Hall and Lutsey, 2017). Further studies are required to develop smart-charging approaches to exploit these benefits.

- A proper EV charging schedule can allocate the charging load to prevent power peaks. EV charging scheduling can play a significant role in mitigating the adverse effects of the vast EV-charging demand without upgrading the power grid capacity. Maintaining grid stability will required vulnerability analysis and risk assessments for a smart EV charging system that consider collecting, distributing, and transmitting real-time data within the network and communicating with other networks. The uncertainty of EV user behaviour poses a challenge to the prediction accuracy of a charging schedule. Machine learning-based methods could be developed to model and predict the EV loads accurately and enable the EV charging scheduling to be optimised to reduce the network impact.

- More research should be conducted on electricity tariff reforms as these also play a significant role in shifting the charging periods from peak to off-peak periods, which would have a substantial impact on grid stability.

2.2.2 System operation and control barriers and opportunities

The power grid's operation and control aspects are affected by EV battery characteristics, charging technologies, location of charging, and the time of charging. The connection of fast and rapid chargers will stress or surpass the network capacity. The increase in the peak load demand is considered to be one of the most significant operation challenges for the power system. It is envisaged that if all vehicles in Australia are replaced by EVs, this would increase Australia's electricity consumption by one third (ABS, 2018).

There is a clear trend towards large range vehicles, larger capacity batteries, fast charging times, and clustering of chargers that can potentially result in adverse impacts on system security, stability, reliability, and overloading of distribution apparatus. Even at today's low EV penetration, coordination and knowledge development are essential to enable the transition towards high EV penetration and avoid duplication cost.

a) Adverse impact of uncoordinated charging of EVs on power grid economics and technical performance

Uncoordinated charging means that EV batteries either start charging immediately when plugged in or after a user-adjustable fixed delay and continue charging until they are fully charged or disconnected (Yilmaz and Krein, 2013a). Uncoordinated charging operations tend to increase the load at peak hours and can cause problems on power grid operation and control (Yilmaz and Krein, 2013a).

The impact on economic costs, emissions, and power network operation and controls depends on EV penetration and charging/discharging strategies. Since expensive fast-start generation units such as gas-fired power stations would need to be deployed to cater for the additional load demand (Dubey and Santoso, 2015), this would increase the power generation cost. Large-scale unregulated deployment could also give rise to a detrimental and destabilising effect on the electric grid (Dubey and Santoso, 2015).

Practical case studies of the problem

In the U.K., a 10% penetration of EVs is shown to result in an increased daily peak demand of up to 17.9%, while a 20% EV penetration would lead to a 35.8% increase in peak load for uncontrolled charging in the distribution system. If the load exceeds peak capacity the utility

operator must increase the peak power generation. Ultimately, these costs are passed on to vehicle owners (Dubey and Santoso, 2015).

Halbleib et al. (2012) have shown that uncontrolled charging could cause an increase in the monthly electricity bill of up to 22% due to demand charges, even at only 10% EV penetration (Halbleib, Turner and Naber, 2012).

Mitigation strategies/solutions

Coordinated smart charging could optimise the charging time and power demand and reduce daily electricity costs, voltage deviations, line currents, and transformer load surges. A coordinated charging system is more suitable for high-power charging levels (Levels 2 and Level 3). Smart chargers provide reactive power support and could therefore be used for providing voltage control services (Zhu, Mather and Mishra, 2020).

Practical case studies of the mitigation strategies

A study conducted in Western Australia has investigated the role of charging coordination in improving the distribution transformer performance (Masoum *et al.*, 2011). While the coordination approach is beneficial in overall system load-leveling and peak-shaving, Van Vliet et al. in the Netherlands showed that off-peak charging would result in a 20% higher, more stable base load without affecting the peak load of the national grid (van Vliet *et al.*, 2011). In a U.K. case study, off-peak charging was shown to increase the electricity consumption throughout the night with no impact on the daily peak load. In fact, when EVs are charged at night (after the night peak hour), the load factor improves as portions of the off-peak valley are filled (Dubey and Santoso, 2015).

b) Difficulties of identifying strategic network locations for fast chargers or charging stations

Charging stations designed for heavy-duty EVs require fast charging rates and would result in large charging demand. Ultimately, this could result in spiky load profiles with large peak loads and extremely high ramp rates (Dubey and Santoso, 2015). Due to the differences in load characteristics and charging behaviour of heavy-duty and light duty EVs, existing investigations are insufficient to understand the grid impacts from heavy duty EV charging stations and fast chargers. High level charging loads of fast charging stations result in increased peak load demand, reduced reserve margins, voltage instability, and reliability problems. Furthermore, the penalty paid by the utility for the degrading performance of the power system also needs to be considered (Zhu, Mather and Mishra, 2020).

Mitigation strategies/solutions

Integrating fast chargers into the network plays a significant role in system's operation (Yilmaz and Krein, 2013a). A systematic methodology for grid impact analysis of heavy duty EV charging stations was proposed by Xiangqi Zhu et al. and considered three major steps: 1) investigation of charging station location, 2) charging load modelling, and 3) grid impact analysis (Zhu, Mather and Mishra, 2020). Charging loads are modelled by a DC fast charging station model, various charging load profiles are connected to different locations in the power system, and the grid impact on different locations is demonstrated on both the IEEE 34-bus test system and a realistic feeder from California. The results demonstrated the voltage impact that the charging station might bring to the system. Based on the analysis of results, a mitigation plan was proposed and tested on the California feeder model using smart chargers. The proposed analysis approach is not system-dependent and can be generalised to other feeders (Zhu, Mather and Mishra, 2020).

The system can withstand the placement of fast charging stations at the strong network connection points up to a certain level, but the placement of fast charging stations at the weak connection points of the system could hinder the smooth operation of the power system (Zhu, Mather and Mishra, 2020). As the impact of the EV charging station loads on the voltage stability, power losses, and reliability indices need to be considered, a strategy for the placement of the EV charging stations on the network was proposed based on a novel voltage stability, reliability, and power loss (VRP) index (Deb *et al.*, 2018).

Practical case studies of the mitigation strategies

An analysis by Xiangqi Zhu et al. showed that using a smart charger reduces the adverse impact of voltage on the grid. A case with strong technical support maintained the voltage within the standard limit, whereas the moderate support case struggled around the minimum limitation edge (Zhu, Mather and Mishra, 2020). The analysis demonstrated the efficacy of the VRP index in finding the most suitable locations for charging stations in the IEEE 33 bus test network. This approach will serve as a guide to power system engineers and help in the planning of distribution networks that factor in EV charging loads (Deb *et al.*, 2018).

c) Impact of uncoordinated and uncontrolled charging of EVs on the power system security and stability performance

Voltage instability is one of the main causes of power system blackouts. The power network is usually operated below the stability limits, with sufficient headroom to manage credible contingencies. When modern technology is introduced to the power grid, it should be compatible with the grid stability boundaries to ensure secure and reliable operation. Additional EV load demand challenges the system stability and security as it stresses the system to its limits.

Practical case studies of the problem

A range of typical faults was investigated, and the critical clearing time (CCT) and transient stability margin used to assess transient stability on the model of the Northern Ireland power system. Simulation results indicate that to achieve and sustain EV integration targets and guarantee adequate transient stability, asset support and network reinforcement will be required (Zhou, Littler and Meegahapola, 2016).

Mitigation strategies/solutions

Using V2G at high charging rates is safe on the power systems from a stability and a power quality point of view. Charging will be directly coordinated by smart metering and by sending signals to the individual vehicles. Coordinated charging of electric vehicles can lower power losses and voltage deviations by flattening out peak power demand. This coordinated charging approach can be quickly adopted and monitored by the operator who prepares the charging–discharging schedule to avoid issues with power quality and disruptive destabilisation while meeting the EVs' charging requirements and satisfying the financial or operational review objectives. Development of smart charging/discharging strategies would assist to achieve economic, reliable, and efficient outcomes for power system operation and control (Zheng *et al.*, 2019).

d) Additional generator start-ups and shutdowns (increased cycling) result in high operating and maintenance cost for generating stations and the lack of flexible generation sources

Depending on the time and place of the EV charging, charging could either require additional power generation sources or increase the utilisation of existing capacity and reduce the reserve

margins. In such cases, generation reliability would be a serious concern (Dubey and Santoso, 2015).

Mitigation strategies/solutions

Implementation of an intelligent EV load management system is necessary to avoid large capital expenditure in network reinforcements and new generation capacity. Intelligent load management system would assist to shift the loads to off-peak periods and reduce the need for generator start-ups and shutdowns.

Practical case studies of the problem and mitigation strategies

Oak Ridge National Laboratory (ORNL) performed a thorough analysis of EV penetration into regional power grids and reported that all regions would need additional generation investment to serve the extra EV demand (Dubey and Santoso, 2015).

Fernández et al. presented impacts of various levels of EV penetration on distribution network investments and incremental energy losses. Depending on the charging strategies, up to 15% of the total actual distribution network costs would need to be invested, and energy losses could increase up to 40% in off-peak hours when 60% of the total vehicles are EVs (Pieltain Fernández *et al.*, 2011).

A comparison of voltage and current violation durations for different EV penetration rates between the heavy and light load scenarios was conducted by Spitzer et al. The results highlighted that the impact of EV charging depends highly on the baseload of the considered grid (Spitzer *et al.*, 2019).

Opportunities for further research from an operational and control perspective

1. Uncoordinated charging could increase peak demand and uncertainty in power grids. This could be potentially detrimental for power system stability and reliability. More research is required to characterise the impact on power grid stability and security and mitigate potential stability threats with high penetration of EVs in the power grid. These studies also need to be interdisciplinary, integrating technical, policy and behavioural aspects.

2. For better coordination and reliability, aggregation needs to be managed efficiently. To maintain grid stability, two-way energy flow and communication between the aggregated vehicles and the grid can be implemented (Yilmaz and Krein, 2013a). Further studies should focus on EV aggregation methods to improve system operation and control.

3. The decreased off-peak electricity rates in a ToU pricing scenario motivate EV owners to charge their vehicles during off peak hours. This method significantly reduces the peak load demand and mitigates transformer overloading and heating concerns (Dubey and Santoso, 2015). Further research could develop effective ToU tariff schemes by considering both system stability/control and social behavioural aspects.

2.2.3 Barriers and opportunities to vehicle to grid (V2G) operation

According to the US Federal Highway Administration, a person travels 13,476 miles (i.e., 22,122 kms) on average annually. This equates to 36.92 miles (59kms) per person per day. In Australia an average vehicle travels approximately 13,301 kilometres per year (36.4kms per day). In order to make V2G technology useful, the vehicle battery has to have sufficient energy capacity for the

daily travel needs and to inject any remaining energy into the grid. The vehicle-to-grid (V2G) technology is an effective and economic solution to enable the integration of EVs into power grids (Zheng *et al.*, 2019).

Studies have shown that EVs could provide ancillary services such as voltage and frequency regulation (primary, secondary, and tertiary control), spinning reserves, reactive power support, peak shaving, valley filling (charging at night when the load demand is low), load following, and energy balance. Based on Energeia's analysis (Energeia, 2017), by 2021 there will theoretically be enough EVs in New South Wales to provide a similar level of frequency control services as the Hornsdale battery in South Australia, assuming all EVs will be V2G capable and enabled for this service (Energeia, 2017).

Vehicle to grid systems can reduce overall costs of service and prices to customers while selling energy to the grid could improve load factors and reduce emissions. These systems could also replace large scale energy storage systems (Yilmaz and Krein, 2013). By employing V2G schemes, electric vehicles could inject power back to the grid during extreme events (to avoid the possibility of blackouts), and EV owners would be paid when their vehicles are used for providing these services. The Realizing Electric Vehicles-to-grid Services (REVS) project demonstrates how commercially available EVs and chargers can contribute to energy stability by transferring power back and forth into the grid as required (Jones *et al.*, 2021).

Vehicle to Grid (V2G) holds the promise of cheap, flexible, and fast-responding storage with electric vehicle batteries. Unfortunately, V2G infrastructure, battery degradation, and consumer awareness are some of the challenges to the faster development of this technology.V2G could also cause a reduction in power quality (e.g., voltage compliance, harmonics) due to the power being injected into the grid via a converter.

a) *Lack of optimal scheduling and controlled charging strategies*

The bidirectional power flow enabled by V2G technology enhances the flexibility for power network operators to control the stored energy in EV batteries and maintain the power network's reliability and efficiency (Habib *et al.*, 2018).

Although V2G systems have many advantages, the growing number of EVs may impact power distribution system dynamics and performance through overburdening of transformers, cables, and feeders. This lowers the efficiency, may require additional generator startups, and produces voltage deviations and harmonic distortion (Yilmaz and Krein, 2012). Fernández et al. presented impacts of different EV penetration levels on distribution network investments and incremental energy losses (Pieltain Fernández *et al.*, 2011).

Mitigation strategies/solutions

More complex smart-charging programs allow the pausing and scheduling of charging and the modulation of charging power to meet the needs of the user and the grid (Hall and Lutsey, 2017). This allows utilities to precisely fit electric vehicle charging into times when the grid has the spare capacity and, in the best case, avoid the need to upgrade distribution network infrastructure or build more generation capacity. There are still technical hurdles to this technology. Most charging stations cannot vary charging current and there are only a few standardised protocols for EVSE-grid communication, although efforts to create standardised interfaces such as ElaadNL's work on the Open Smart Charging Protocol are in progress (Hall and Lutsey, 2017).

Practical case studies of mitigation strategies

Numerous studies have analysed the potential for controlled charging to alleviate grid congestion concerns, with very convincing results. The Sacramento Municipal Utility District estimates that one-way smart charging will reduce grid upgrade expense by over 70%, and the Green e-Motion project found that when using smart charging, network reinforcement costs in the European Union dropped by 50% while also reducing greenhouse gas emissions. Most ancillary services could be provided with this form of smart charging without causing any additional stress on batteries or requiring additional hardware in the vehicle (Hall and Lutsey, 2017).

b) Premature degradation of batteries and concerns of vehicle owners

Bidirectional charging (V2G, V2H, etc.) is the concept of charging and discharging an EV battery in order to serve a secondary purpose (e.g., voltage and frequency control of the power grid). All batteries age with usage and time. This means that the amount of energy a battery can store or the amount of power it can deliver will be reduced over the time as the EV ages, leading to lower capacity and performance. Battery degradation is measured by evaluating two primary factors: calendar fade and cycling fade (Stroe *et al.*, 2017). Calendar fade refers to the degradation caused by storage, while cycling fade is caused by the number of charging and discharging cycles of the battery. The most common factors that contribute to battery degradation are the temperature, C rates, state of charge (SoC) and (depth of discharge) DoD levels (Schimpe *et al.*, 2017).

Extreme low or high temperatures severely increase battery degradation while good performance is likely to be achieved at an ambient temperature of around 25˚C. Increasing C rates (charging or discharging current) reduces battery cycle life. Both storing a battery at a high SoC and deeply discharging a battery can significantly reduce its cycle life (Jones *et al.*, 2021).

Practical case studies of the problem

Increasing the ambient temperature from 25°C to 35°C would reduce the battery life by nearly half – from 102 months to 58 months – when providing frequency regulation services (Stroe *et al.*, 2017). M. Schimpe and colleagues found that both high and low temperatures will lead to high-capacity loss, with the optimum temperature being 25°C (Schimpe *et al.*, 2017).

Mitigation strategies/solutions

Smart charging and optimised V2G would reduce battery degradation. Battery pack temperature management and SoC management are also effective methods to reduce battery degradation when operated in V2G mode. Li-ion batteries are the best candidate for V2G because of their long lifetime reasonable deep-cycling capability, high energy density, and high efficiency (Yilmaz and Krein, 2012).

Practical case studies of the mitigation strategies

Petit et.al concluded that charging in the morning, just before a vehicle's first trip, significantly improves battery health compared to charging in the evening. Their study also found that frequent charging (charge when you can) leads to greater battery degradation (Petit et al., 2016). Fast battery degradation occurs at high or low SoC. Keeping SoC in the range of 70% to 90% and charging throughout the night increases the battery life by approximately 1.8 years compared to un-optimised charging. This is validated against the degradation model developed by NREL. It has also been shown that reducing cycle depth from 90% to 70% increases battery life by 8-10 months when providing frequency regulation services (Schimpe *et al.*, 2017).

c) Increase of transformer cyclic/non-cyclic heating (due to abrupt bidirectional power flows) and degradation of their lifetime

In the construction of substations, distribution transformers are planned and designed without considering the large charging demands from EVs. Predictably, clustering heavy EV loads in residential distribution grids it would increase the hot spot temperature of the transformer and accelerate the transformer's ageing (Habib *et al.*, 2018). This would lead to the increased risk of transformer failure (Habib *et al.*, 2018).

Practical case studies of the problem

In a study conducted as part of the National Household Travel Survey, Razeghi et al. 2014 found that uncontrolled charging has a little effect on transformer lifetime with Level-1 charging (i.e., 1.44kW) whereas it will result in extremely high ageing rates and even transformer failure at Level 2 (i.e., 7.2kW) (Razeghi *et al.*, 2014). Uncoordinated charging behaviour would also increase the burden on-line loading (Zheng *et al.*, 2019).

Excessive uncontrolled charging of EVs will reduce the life-span of a transformer. Uncontrolled charging of EVs has, for instance, caused 15kVA and 25kVA transformers to break down and lead to fires in the outskirts of Los Angeles and Vermont (Habib *et al.*, 2018). Designing appropriate charging methods and charging infrastructure for EVs will be critical to improving the life span of transformers (Habib *et al.*, 2018).

Mitigation strategies/solutions

Degradation of the life of a typical distribution transformer can be reduced by using a controlled charging scheme (Yilmaz and Krein, 2012). The decreased off-peak electricity rates in a ToU pricing scenario motivates EV owners to charge their vehicles during off-peak hours. This method significantly decreases the peak load demand and mitigates transformer overloading and heating concerns (Dubey and Santoso, 2015).

Opportunities for further research from a vehicle to grid (V2G) operation perspective

Smart charging and discharging (Smart V2G) have a strong potential to increase the support provided to the grid and could particularly alleviate potential instability issues, transformer failures, and premature battery degradation. However, further studies are required to better understand how to deploy smart V2G methods to improve grid stability and reliability.

2.2.4 Barriers and opportunities to EV orchestration with distributed energy resources

If renewable energy sources are used properly to charge EVs by overcoming the barriers mentioned below, smart V2G provides an even stronger potential for demand response to further reduce the peak-load and increase asset utilisation of the network (i.e., relieve the network congestion). That would improve the reliability and resilience by providing a variety of ancillary services, including voltage control, frequency regulation, and spinning reserves to the grid.

a) *Potential impact on grid stability and power quality due to the intermittent nature of PV energy and uncertainty of EV load*

Individually, PVs and EVs can negatively affect the grid stability and power quality due to the intermittent nature of PV energy and uncertainty of EV load. However, several research studies have reported that coordinated operation of PVs and EVs can negate such issues. Integration of PV systems may pose both negative and positive impacts on the power grid operation depending

on the PV penetration level, system topology, location of PV integration, type and location of the disturbance (e.g., a fault or loss of a generator) experienced by the grid. Furthermore, large-scale penetration of PVs and EVs is expected in the future, and the coordinated operation of EVs and PVs can help lower energy costs and carbon footprint (Harvey, 2018).

Practical case studies of the problem

Onar and Khaligh et al. investigated the impact of EV-integration, associated current harmonic injections and reactive power consumption on distribution network stability. The results showed that stability deteriorates and recovery time to reach steady-state conditions increases (Onar and Khaligh, 2010).

Mitigation strategies/solutions

Smart chargers and intelligent energy management systems are able to effectively integrate renewable energy with the EV load. The grid codes to improve system reliability with PV have been developed in a number of countries including South Africa, China, Germany, and the US.

Practical case studies of the mitigation strategies

To better utilise the benefits of solar energy and ensure seamless participation of PV systems in grid frequency regulation, Remon and colleagues proposed synchronous power controllers (SPCs) that ensure harmonious interaction of PV system with the grid. The results of the study demonstrated that the SPCs can limit frequency deviations, improve the oscillation damping, and reduce the stress on the other generating units following a grid disturbance (Remon *et al.*, 2017).

Wu et al., proposed an application of superconducting magnetic energy storage (SMES) alongside EVs to enhance the transient stability of the power grid (Wu, Inderbitzin and Bening, 2015). Tabari and Yazdani also proposed a non-linear control approach that can coordinate EVs in a DC distribution network so that the stability of the distribution network could be enhanced (Tabari and Yazdani, 2015).

b) Volatility and intermittent nature of DERs (i.e., solar-PV) and a lack of appropriate forecasting models for distributed DERs

Power generation from wind and solar-based renewable energy resources (RES) is typically unpredictable and varies with weather conditions. Power output variation of PV systems could result in voltage fluctuations which exacerbate when PV penetration increases. This effect is more prominent when a large-scale PV system is connected near the end of long, lightly loaded feeders (Harvey, 2018).

Mitigation strategies/solutions

Orchestration of EVs with DERs is an emerging alternative to resolve issues emanating from the variable nature of RES as EVs could be pooled to provide flexible storage capacity to firm up the PV output power (Hussain *et al.*, 2021). In a smart grid environment, EVs become a possible solution to the challenge of balancing the power fluctuations caused by the intermittent nature of RES. Demand and generation must be perfectly matched and continuously managed to avoid any frequency instability issues in the power grid (Hussain *et al.*, 2021).

Smart V2G charging and discharging, in which EVs are charged from renewable resources and discharged to the grid at peak load conditions, have been reported to offer the best potential to utilise renewable sources to reduce cost and emissions (Hussain *et al.*, 2021). Smart metering

infrastructure and a control system must be implemented to combine EVs and renewable energy to achieve peak shaving (Hussain *et al.*, 2021).

The study found that centralised coordination is the best management strategy to solve issues of EV integration into the power grid. The centralised coordination with integration of renewables optimises the overall production cost of the system and the charging cost to EV users. Vehicle-to-grid coordination (or Smart V2G) solves the intermittent nature of renewables by storing excess energy into EV batteries during off-peak hours and supplying energy during peak hours. Optimal techniques in centralised coordination schemes determine accurate battery capacity and best charging location with less computation time (Hussain *et al.*, 2021).

Practical case studies of the mitigation strategies

A study conducted in Canary Islands found that assuming a certain threshold of V2G usage in tandem with pumped hydro storage could reduce energy dependency while increasing the renewable share of generation, reducing carbon emissions (Sovacool *et al.*, 2018).

The large-scale deployment of parking lot solar car chargers was analysed by Neumann et al. This study introduced solar carports over all available large parking lots in a medium-sized Swiss city and found that 14–50% of the city's passenger transportation energy demand could be provided through solar energy with the proposed system (Harvey, 2018). Directly charging vehicle batteries with solar PV panels would allow EVs to be charged using electricity generated on-site, thus avoiding transmission losses from distant power plants or wind farms. Furthermore, converting the DC solar electricity to the AC grid could result in energy losses of around 10% which can be avoided by directly charging the batteries from PV panels (Harvey, 2018).

Opportunities for further research in EV orchestration with Distributed Energy Resources

Further studies are required to optimally orchestrate EV charging and discharging with DERs to reduce DER's curtailment (under high penetration), peak shaving, and achieve energy cost optimisation to EV customers.

2.3 Review of Policy Regulatory Framework

2.3.1 EV adoption policies, directives, and targets of countries and regions

Regulatory barriers are sometimes more challenging than technology barriers. The following factors must be taken into consideration when developing policies to facilitate EV adoption: financial support schemes for EV purchases, EV-supportive electricity pricing schemes, and encouraging DNSPs to take an active role in deploying charging stations across their networks.

Countries committed to expanding their EV penetration levels have set objectives to improve air quality in vehicle-dense urban areas. Developing policies to reduce the public transportation sector greenhouse gas (GHGs) emissions and reduce foreign oil imports would therefore stimulate the EV market (Bradley, 2013). Most of the countries, such as Norway, Finland, United Kingdom, Italy, Ireland, China and the U.S.A. already have their own economic incentive policies in terms of tax incentives, subsidies on registration taxes, and local incentives like free access on state ferries, bus lanes and toll roads and so on. These policies have led to the rapid adoption of EVs. Petter Haugneland and colleagues suggest introducing a small carbon tax on fossil cars based on emissions levels and to use the revenue to fund EV incentives until the EVs can compete without such compensation (Haugneland *et al.*, 2017).

Australia also has a number of strategies and policies relevant for EVs at state-level and local government-level, ranging from reduced or waived stamp duty (ACT, Queensland, New South Wales, Victoria) to subsidies (New South Wales, Victoria) and rebates on EV charging stations (City of Adelaide) (Dwyer *et al.*, 2021). These strategic policy initiatives are likely to increase EV adoption in Australia in the next few years despite no strong EV adoption policies yet being implemented by the Federal Government.

a) Lack of long-term planning and goals, such as integrated system/energy plans for EV grid integration, by regulatory regimes

Appropriate long-term planning regimes must be implemented to align policies with the goal to increase EV ownership. These must look at vehicle technologies, driver behaviour, evaluation of different methods of EV charging methodologies, business models, electricity markets, and grid operations. Better alignment of electricity and transport planning processes will be essential to optimise grid integration of EVs, mitigate risks, and capture as much value as possible for customers and system operators.

Recommendations:

Policies could be set for developing charging stations with a minimum number of fast chargers to solve vehicle range issues. This would allow drivers to charge their vehicles while travelling. Sufficient fast chargers could reduce range anxiety and mimic the refuelling infrastructure to which drivers of gasoline-powered cars have become accustomed. Deregulation of the electric sector in all regions will facilitate greater market-based procurement of decentralised generating capacity and load management resources. This will result in more opportunities for EVs to provide valuable services to the electric grid (Bradley, 2013).

b) Lack of country-specific studies and EV grid integration forecasts

Electric sector environmental regulations in the United States, coupled with low natural gas prices, have helped to reduce emissions from power generation, improve the operating footprint of EVs, and increase their comparative advantage over gasoline-powered vehicles. Electric sector regulations in the U.S. and decarbonisation goals implemented in the EU continue to reduce GHG intensity and conventional air emissions from electricity generation (Bradley, 2013).

Recommendations:

Policy objectives must limit adverse grid impacts, realise the full potential of grid benefits, expand economic incentives to drivers, and avoid creating stranded assets through subsidies (Bradley, 2013).

c) Lack of encouragement on designing new electricity market mechanisms and tariff structures for promoting G2V and V2G

Research institutions, utilities, EV-equipment supply chains, industry bodies, and the automotive industry should collaborate to establish standards that effectively utilise managed charging programs to empower EV users while also benefiting the electric power grid. Regulatory procedures and policies for commercial firms are needed in the distribution market (Ashique *et al.*, 2017).

Many electricity regulators have implemented or considered customised pricing of electricity for EV owners. Some pricing schemes provide discounts to EV owners while others merely create tiered pricing to more accurately reflect the varied costs of generation over the course of a day

(ToU pricing). Discounted pricing provides a direct incentive by lowering charging costs; TOU pricing provides an incentive to charge at off-peak times of the day and may lower charging costs, depending on charging behaviour.

Recommendations:

New regulations are required to impose transparent service remuneration of all services. Transparency would enable economic calculations to provide the basis for a flexibility price and the introduction of local flexibility trading platforms (Knezović *et al.*, 2017).

Electricity tariffs should be revised to include both a capacity and an energy component. Such a tariff would encourage EV user participation in flexibility schemes as the EV is a significant load compared to other residential appliances. A revised tariff could incentive a decrease in peak power, by encouraging EV owners to allow control of the charging to minimise peak demand. Another aspect that needs to be considered is the regulatory period (Knezović *et al.*, 2017).

Offering a dual tariff (cheap night rates) to reduce peak load would encourage EV owners to use time-variable rates with Level 1 or 2 charging. This would motivate EV owners to wait for cheap off-peak prices that generally occur during the night when the load demand is lower (Haidar, Muttaqi and Sutanto, 2014).

d) Lack of policies to encourage smart charging and EV aggregation

Governments have supported developing a basic charging infrastructure (e.g. Lorentzen *et al.*, 2017). However, charging capacity substantially differs based on the state of charge, battery temperature, and the on-board charger of different EV models, and this variable capacity is not reflected in the current kWh-based charging method. The limitations of this infrastructure must be taken into consideration when designing EV charges, with a combination of time and kWh, similar to taxi rates with a variety of time and kilometres (Lorentzen *et al.*, 2017). Therefore, EV charging pricing policies should be set to reflect on these dynamic effects, hence it would encourage smart charging.

Recommendations:

Regulations need to allow the aggregation and procurement of EV flexibility services. Even where regulations currently do not encourage flexibility procurement, they should be revised to explicitly allow it so that the DSO can directly invoke EV flexibility for a fixed price if this is assessed to be the most cost-efficient solution (Knezović *et al.*, 2017).

Policies could be adopted to reduce the impact of EVs on networks and to meet the energy security targets by maintaining a balance between generation and load demand. Policies such as mandating a smart energy meter at the EV customer premises would allow the control of EV battery smart chargers. This would mitigate the problems associated with power quality during bidirectional charging and contribute to the efficiency and reliability of electric mobility in smart grids (Haidar, Muttaqi and Sutanto, 2014).

In the Australian context, smart charging and smart V2G concepts are still new. However, Adelaide City Council has already implemented various incentives for smart charging and V2G-

enabled charging stations to encourage EV charging station owners to adopt these technologies.[5]

2.3.2 Policies and regulation of public transport and service fleet electrification

a) Lack of economic incentives in terms of relaxations of charges on toll roads, ferries, and parking, provision of access to bus lanes, exemptions in driver's license fees, fiscal compensations etc.

The introduction of EVs into the transportation sector dramatically expands the purview of electric sector regulators.

Recommendations:

As electric sector regulatory decisions begin to intersect with transportation planning, it will be important to align policies from both transportation and electric system planners in all regions to facilitate market growth. Electric sector regulators play an essential role in ensuring reliable electricity supplies and protecting consumers from monopoly pricing, while market regulators oversee policies that directly impact EV adoption (Bradley, 2013).

Progressive tax systems (e.g., in Norway) make most EV models cheaper to buy than a similar petrol models, even if the import price for EVs is much higher. This is the main reason why the Norwegian EV market is booming compared to other countries (Haugneland *et al.*, 2017). Even if the CO_2 tax is not directly earmarked to fund EV incentives, the total income of the tax is more than the cost of EV incentives, with a 16% EV-market share in Norway in 2016. This model could be adopted elsewhere to increase the market share for zero emission vehicles to reduce CO2 emissions and local pollution.

b) Lack of awareness about transforming vehicle fleets

An array of multi-national, national, state, and city incentives across the regions have stimulated the EV market by reducing purchase costs, streamlining electricity pricing, lowering charging costs, subsidising EV infrastructure, and creating mandates and markets for emission reductions from transportation and electric power generation.

A number of governments have demonstrated a commitment to EVs by providing financial support for EV purchases, implementing EV electricity pricing schemes, and encouraging DNSPs to deploy charging station networks. The option of subsidising the build-out of EV charging stations is the subject of ongoing debate in all regions.

Education programs, field days, and the media play an important role in diffusion of information about EVs as customers need to be persuaded to make the change when innovative products such as EVs are not direct substitutes for the incumbent technology. The media was the most important source of information for Norwegian EV owners. Norway has had a sustained program of promoting EVs for about 20 years, giving it time to build awareness (Broadbent, Drozdzewski and Metternicht, 2018).

Government procurement of EVs for its fleets is important in stimulating demand and assisting in creating a second-hand market relatively quickly, and it also enables drivers to get EV

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[5]   https://www.cityofadelaide.com.au/about-council/grants-sponsorship-incentives/sustainability-incentives-scheme/

experience without having to buy an EV (Broadbent, Drozdzewski and Metternicht, 2018). For Australia, local governments in particular have an important role to play in the deployment of EV charging networks due to their responsibilities (for instance, managing local road infrastructure) and the local in nature benefits (such as improved air quality) (Dwyer *et al.*, 2021).

2.3.3 Existing government incentives to promote EV adoption in private sectors

a) Absence of policies on annual tax exemptions for EV owners

Governments can implement policies to encourage the uptake of a new technology. Policy approaches can be statutory, market-based, or simply provision of information. Market formation policies may contribute to higher shares of EV sales (Broadbent, Drozdzewski and Metternicht, 2018). The existing policies set by many governments focus on reducing the purchase costs directly (e.g., through rebates), increase the useful range (e.g., through subsidised networks of high-capacity charging stations), and provide EV drivers with preferential access to roadways (e.g., through exemptions to registration caps). Nevertheless, sales of EVs have fallen short of both governments' and manufacturers' goals, suggesting that current incentives are insufficient to break down the barriers to market growth. According to the Norwegian EV owners survey 2017, economic incentives are the most compelling approach to convincing people to try out a new emission-free technology (Haugneland *et al.*, 2017). More economic incentives should be put in place to expedite the EV adaptation.

Recommendations:

By creating exemptions to registration fees and permitting quotas, governments can encourage buyers to choose EVs over ICE vehicles. Commitment to EVs could be increased by providing financial support for EV purchases, implementing EV electricity pricing schemes, and encouraging LDCs/DSOs to take an active role in deploying charging station networks.

A chief focus of EV policies has been to offset high costs and usability limitations ((Bradley, 2013).

b) Lack of purchase subsidies

Government and corporate vehicle purchases account for a significant share of market activity around the world. For example, in 2011 approximately 19% of total passenger car sales in the US were fleet purchases. In Germany, that number is 32%. Shenzhen has an EV fleet made up of 1,300 public buses, 700 taxis and roughly 1,000 private EVs. In May 2013, the Chinese EV maker BYD announced that in the U.S. its e6 will be sold only to fleet customers where it sees the most significant market potential.

Recommendations:

Fleet-focused incentives and policies may provide municipalities and governments with an efficient tool to increase EV penetration (Bradley, 2013).

Opportunities for further research

1. Further research must be conducted on designing integrated energy plans that consider EV adaptation. These plans should factor in future EV uptake by using more reliable EV forecasts.

2. Studies should be devoted to developing fleet-focused incentives and policies to increase electric vehicles in the public transportation sector.

3. More grid-friendly tariff structures should be developed for EV owners that take into account renewable energy production and user behaviour.

2.4 Review of standards and grid codes

A unified and consistent worldwide standard for EV grid connection is important for the worldwide adoption of EVs. Some aspects of EVs, such as charging plugs, voltage chargers, contact between the vehicle and the chargers, fast and slow charging systems, safety measures for the safe operation of the vehicle and protection from electrical shocks, and on-board electrical energy storage for the vehicle need to be standardised for the safe and reliable use of EVs. This literature review will present the existing studies, research, standards, and grid-codes available in different jurisdictions. The review will consist of two parts: (1) barriers and opportunities: EV grid connection standards, and (2) barriers and opportunities: adaptation of grid codes for EV adoption.

2.4.1 Barriers and Opportunities: EV grid connection standards

Standards for electric vehicle charging

There is a range of internationally-relevant standards for EV charging systems, including SAE standards, IEEE standards (which are mostly used in North America), and IEC standards (commonly used in Europe). Japan, however, has its own EV charging standards (CHAdeMO), and China has adopted the Guobia (GB/T) Standard (issued by the Chinese Standardisation Administration and the Chinese Provincial ISO and IEC Council). The different standards are coded according to the organisations that created them. Foley, Winning and O'Gallachoir (2010) show that there are only three grid integration codes available so far.
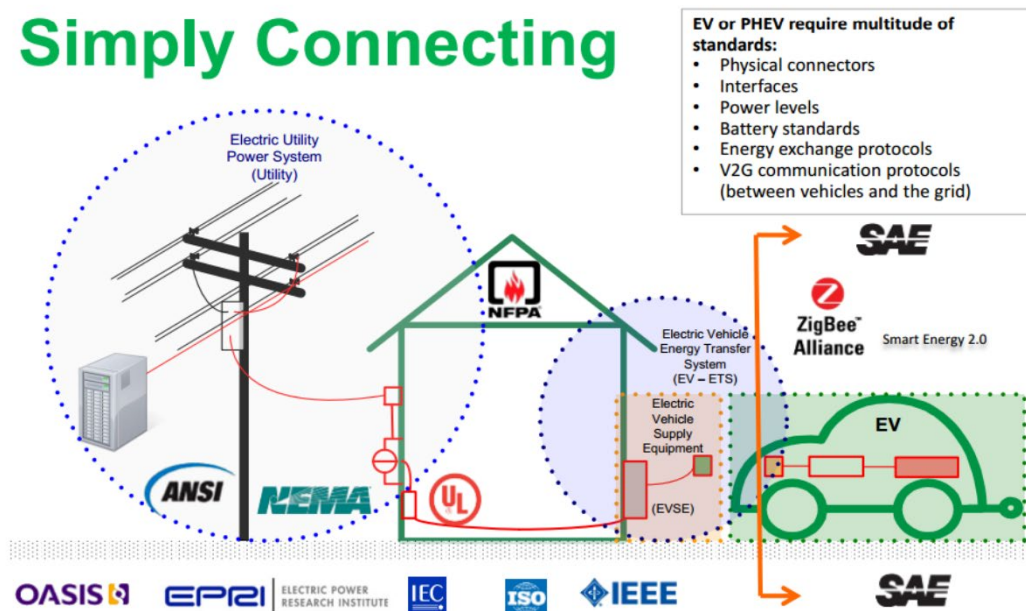

Figure 21. Implemented international standards for EVs (Habib *et al.*, 2018)

The three most widely accepted EV grid connection standards, SAE, IEEE and IEC, have been summarised below:

SAE Standards

The SAE (Society for Automotive Engineers) is a USA-based professional organisation that sets standards for technicians in various automotive industries. The following standards constitute the basic rules for EV grid connection standards:

- **SAEJ1772** refers to the standard signified for customary requirements of EV conductive charging system and charger couplers. This code refers to the EV conductive charging system consisting of operational, functional, and dimensional fundamentals for vehicle inlet connectors.

- **SAE2847** and **SAE2836**, along with **SAEJ1772**, define the connectivity specifications between the EV and the charging network.

- **SAEJ2847** outlines the communication criteria and **SAEJ2836** describes the usage cases and provides the test infrastructure (Pereirinha and Trovão, 2011).

- **SAEJ2931** specifies the requirements for digital communication between EVs, EVSE (Electric Vehicle Supply Equipment), utility, energy service interface, advanced metering infrastructure, and home area network (Pereirinha and Trovão, 2011).

IEEE Standards

The IEEE (Institute of Electrical and Electronic Engineers) Standard Association (IEEE SA) facilitates the development and modification of IEEE standards. Some insights from the IEEE standards into the recommended practices applicable to EV charging and grid connection are provided below:

- **IEEE 2030.1.1** specifies the implementation structure for electric vehicles and direct current (DC) fast chargers which enable the interoperability and rapid charging of electric vehicles. Future iterations of the standard will include additional design requirements to consider recent technical developments in the field of bidirectional charging (V2X), ultra-fast charging of up to 400kW, and smart (dynamic control) charging.

- **IEEE1547** refers to the standards reflecting the 'Interconnection of Distributed Energy with Electric Power Systems.' It applies to all DER technologies with a total capacity of 10MVA, includes performance, service, monitoring, protection requirements and maintenance parameters for DERs, and promotes the implementation of DERs at both primary and secondary level.

IEC Standards

The IEC (International Electrotechnical Commission) is a European-based international standardisation body that is expanding standards for electrical, mechanical, and other associated technologies (Pereirinha and Trovão, 2011). The following IEC codes are relevant to the EV grid connection standards:

- **IEC 62196** offers a standard for plugs, socket-outlets, vehicle connectors, and vehicle inlets that are mandated for conductive charging of EVs as (Kusakana, Munda and Jimoh, 2009). There are three parts in this standard: (a) Part 1: General requirements, (b) Part 2: Dimensional compatibility and interchangeability requirements for a.c. pin and contact-tube accessories, and (c) Part 3: Dimensional compatibility and interchangeability requirements for DC and AC/DC pin and contact-tube vehicle couplers.

- **IEC 61850-x** refers to communication networks and electric utility control scheme standards (Kusakana, Munda and Jimoh, 2009).
- **IEC61851** represents the overall standard operation of EV conductive charging systems which applies to on-board and off-board devices as Part 24 (Kusakana, Munda and Jimoh, 2009) [45]: Digital communication between a DC EV charging station and an electric vehicle for control of DC charging.
- **IEC 61439-7** denotes standards for Low voltage switchgear and power gear assemblies (Kusakana, Munda and Jimoh, 2009).
- **IEC 61980** addresses standards for electric vehicle wireless power transfer systems (WPT): Part 1: General requirements.
- **IEC 61851-1** only offers standards for electric vehicle conductive charging system as follows: (a) Part 1: General requirements, (b) Part 21: Electric vehicle requirements for conductive connection to an a.c/d.c. supply, (c) Part 22: AC electric vehicle charging station, (d) Part 23: DC electric vehicle charging station IEC 61980 addresses standards for Electric vehicle wireless power transfer systems (WPT) (Kusakana, Munda and Jimoh, 2009).
- **IEC 60364-7-722** represents the standards for Low-voltage electrical installations as **Part 7-722:** Requirements for special installations or locations - Supplies for electric vehicles (Kusakana, Munda and Jimoh, 2009).

Barriers in EV Grid Connection Standards

- Lack of coordination of standardisation requirements/ rules in different layers of the electrical grid network including end-user electrical infrastructure and poor defining of standards (Saldaña *et al.*, 2019).
- Standardisation limitations on hardware and software for charging stations (barrier to lower equipment costs and the use of smart charging) (Hall and Lutsey, 2017; Saldaña *et al.*, 2019)
- Lack of standards on electric vehicle charging infrastructure and their grid integration (LV/MV) requirements (e.g., charging stations; smart charging) (Saldaña *et al.*, 2019).

Opportunities for further research

- Review and recommendation of the standardisation requirements that would be the most suitable for Australia in different layers of the electrical grid network (including end-user electrical infrastructure and defining of standards)
- Identification of suitable standardisation of hardware and software for charging stations (to achieve lower equipment costs and the use of smart charging)
- Identification of suitable standards on electric vehicle charging infrastructure and their grid integration (LV/MV) requirements (e.g., charging stations; smart charging).

2.4.2 Barriers and Opportunities: Adaptation of grid-codes for EV adoption

All electrical apparatus and systems that are operating within the electrical power system are governed by rules that are specified by the system operators, known as grid codes. This section particularly discusses the grid codes relevant to (1) general charging, and (2) high power charging.

Charging of electric vehicles

The following grid codes provide an outline of the requirements for conductive charging with alternating current (AC) and direct current (DC) and assign them to the respective technical components.

- The standard **IEC 61851-23** was developed for DC charging systems, defining the charging process and other special specifications.
- The AC charging connector systems necessary to connect an electrical vehicle to the infrastructure are specified in **IEC 62196-2**. The DC connector systems are governed by **IEC 62196-3**. Both specifications are subject to the general criteria set out in **IEC 62196-1**. The connector systems mentioned in these requirements are part of the Combined Charging System (CCS) and have already been established as the minimum charging point equipment in publicly accessible areas in EU Directive 2014/94/E (German National Platform for Electric Mobility (NPE), 2020).

High power charging

The desire for better long-distance efficiency is predicated on the use of higher-capacity battery solutions and the need for faster charging. An increase in charging strength poses a major issue for standardisation experts. The charging protocol must be compliant to ensure that the necessary charging infrastructure can still be used for the connector systems. The connector devices therefore cannot be heavy or bulky and must remain easy to accommodate by all users of the vehicle. In addition, all electrical safety standards must be met, even with considerably higher charging capacities (NPE, 2020).

Barriers in EV grid connection standards

- In order to make EV distribution grid services possible, deployment of infrastructure with embedded intelligence should be supported and promoted by standards and regulations (Knezović *et al.*, 2017; Habib *et al.*, 2018).

- The current NER requirements can be a barrier to grid services from distributed resources, including V2G in Australia (Jones *et al.*, 2021); NER rules need to be changed.

Opportunities for further research

- Identification of the suitable EV grid codes to be compatible with all relevant Australian grid codes and standards.

- Identification and proposition of the consistent and coherent EV grid codes that are compatible with the national electricity rules (NERs).

3. Urban design and distributed grid management

Australia is significantly lagging behind other developed economies in its uptake of EVs, both in percentages and growth. Electric vehicles account for 0.7% of total Australian car sales compared with 10% in the European Union and over 8% in California (Fernyhough, 2021). In this review on barriers associated with urban design and distributed grid management, our interest is in how a deeper understanding of the interaction of energy, transport, and urban design can assist in the transition to electric transportation, factoring in the role of renewable-powered microgrids in cities, at the edge of the grid, and in remote locations.

Additionally, the transition to decentralised renewable energy generation and storage (including household, vehicle, and deep storage options) is inevitable and will provide cheaper electricity and storage. This affordability will drive rapid uptake of such technologies, which, if not managed effectively, will affect the stability and reliability of the grid. This calls for careful consideration of how to respond. Newman (2020) notes that an *ad hoc* approach is likely to lead to more automobiles on the roads as the uptake of private EVs increases, if not complimented by the strategic deployment of shared and transit EVs and electric micro-mobility.

Current electricity grids are not prepared for the transition from a centralised system to a decentralised system with varying, bidirectional flow. A range of barriers need to be overcome to implement such new approaches to a Distributed Energy Resources (DER) transition, and these will differ between in cities where urban design is significant, in edge of grid use, and in remote electricity networks.

In cities, urban design and development considerations include transition rates, land use for transport planning, consumer equity, business models for transit EVs and related urban development, battery optimisation, electric bus integration, and consumer behaviour. Edge of grid barriers are business model development, microgrid control and localised generation and storage balance. Remote grid considerations include the scaling of EV storage, cost of independent micro-grids, integration with hydrogen technology, and increased dependence on vehicle logistics. The review of barriers is divided into these three areas. As part of this review, we have also provided summaries of relevant research papers pertaining to each barrier (in Appendix 3).

3.1 Barrier: Urban design and development in cities

Electric vehicles, whether small private vehicles, larger vehicles such as buses and trucks, or new categories like trackless trams can be thought of as mobile batteries of different sizes. Where they park or stop, where they connect to charge or supply energy, and their routes all depend on, and influence, urban design. These mobile batteries can be both an important stabiliser for the grid to account for fluctuating renewable generation or, equally, another source of fluctuating demand or excess supply. Microgrids, generally solar powered, and incorporated into the urban fabric with stationary storage, have a role to play in removing pressure from the grid. Further, while EVs have lower emissions impact, the rapid growth of electric cars due to cheap solar and batteries may make cities very dysfunctional from increased traffic and urban sprawl and increase the need for more energy. However, if electric transit is prioritised it can reduce the energy demand and enable regeneration of older suburbs with decarbonisation of station precincts using recharge facilities associated with microgrids.

Key barriers identified include a lack of understanding of the pace of transition to electrified transport and renewables, equity, business models for EVs on the grid, business models linking

to urban development, and the value and revenues EVs can create. Also identified were a lack of integrated land use and planning, poor adaptation of public transport to electric buses, lack of clarity on behavioural aspects of EV use and on the optimal mix of batteries for stationary and mobile batteries of different sizes to support microgrids. Opportunities were also seen for the use of large parking areas for solar generation and energy storage in peri-urban and outer-suburban areas. The lack of integration between land use and transport planning is a barrier to creating transit activation of new urban regeneration opportunities using 21st century decarbonisation technologies in shared precincts. Overcoming this could potentially make more reliable, affordable and cleaner grids once the benefits are properly understood. So far, exploring good integration is lacking in the literature, especially the interplay of energy, transport and urban design. Some aspects relevant to understanding this interplay have received attention and are described following.

How and where *to* deploy charging infrastructure in the urban fabric has been investigated by several authors. Wei et al. (2018) explored how to stage deployment of charging for electric buses in a way that is economically viable and accounts for current range limitations. Unsurprisingly, economic deployment is best in denser urban precincts. Al Awadhi, Moumouni and Khodary (2019) show that linking microgrids to precincts requires coordinating large public parking areas as solar storage and back-up coupled with incentives for bidirectional charging at suitable times of day. During work hours, cars will be densely packed into such hubs where they are located near train stations, causing charging hotspots. Unless PV capacity across the grid is channelled to these hotspots, solar charging potential may be lost. The opportunity for substantial V2G through stationary vehicles over long periods makes these sites potentially high priority areas for demonstrations

Another aspect is equity. Not all people are equally able to access rooftop solar, afford EVs, or live in areas where chargers are deployed. Sheldon and Dua (2019) propose innovative incentive schemes for EV uptake that vary according to wealth and income, showing how to best use government funds to achieve desired policy objectives. Chung, Park and Kwon (2018) showed that constraints were needed to ensure that chargers were not only deployed in dense urban areas but also in less dense and possibly poorer areas. The relationship across driving behaviour and vehicle range, energy cost and charging dynamics has been explored and modelled by Sohet (2020). While the modelling relies on data, market conditions, and technology from 2020, it should hold as range increases, energy cost (due to solar) decreases, and charging times decrease. He, Yin and Zhou (2015) explore how charging locations must also account for driver spontaneity and risk appetite rather than traditional traffic modelling approaches.

Business models associated with EVs, charging, and urban development have been explored from a few angles. The growth of EVs on the grid means we need to develop suitable business models and the policy frameworks and regulations to support such models, which will be important to attract new investment. This will apply first to large fleets, and particularly to bus fleets, as they electrify and need recharge services at depots. The consensus is that larger collections of co-located chargers in denser areas provide the best economics. Comodi et al. (2016) show how, given EU incentives, utilities can invest in building charging stations and receive payback in 4-9 years and also noted the extreme sensitivity of EV uptake to vehicle price. Noel and Sovacool (2016) explored how The Better Place model (swappable EV batteries to facilitate rapid refueling) failed due to the assumption that range anxiety was the overriding factor holding back EV uptake. Other studies have shown that the most profitable approach for public charging stations is to charge vehicles as quickly and promptly as possible but also apply

some simple incentives to avoid peaks in numbers of vehicles charging at once (Brandt, Wagner and Neumann, 2017). Research undertaken by UTS with local government revealed a focus on achieving best value for money with maximum community benefit while avoiding stranded assets and negative impacts on groups or individuals (Dwyer *et al.*, 2021).

Detailed economic optimisation models for charging and storage infrastructure were developed by Bandyopadhyay et al*.* (2020). This included optimising the PV/battery/grid sizing accounting for tariff regimes and solar potential. Further, the proliferation of small-scale generation and storage brings new opportunities for energy services, but it is unclear how such business models impact and enhance urban development without some kind of intervention to facilitate solar transit- oriented development rather than solar-EV oriented urban sprawl. Related to this is underestimating the rate of transition to renewables and electromobility. Countries with high penetrations of renewable energy are already experiencing grid stability and control issues and developing energy surpluses (Rawat *et al.*, 2019). This lesson from renewables should be learned for when EV prices hit parity with ICE vehicles and there is a rapid uptake of EVs and concomitant potential increase in load and generation fluctuations.

Research opportunities

Thinking ahead: Much of the literature analyses an environment where EVs have limited range, charging is slow, and the grid has not properly adapted to the majority of generation being renewable and increasingly distributed. In the medium term this is likely to change, and research assuming that these things *will happen* may have more impact and provide better guidance in planning, deployment, and policy making.

Linking Energy, Transport and Urban Design: The literature is rich in the links between any two of these areas but lacking in the area of understanding the interplay of all three. Exploring this interplay, combined with *Thinking Ahead* should provide high impact research topics. One of the themes in energy is the move to distributed energy and microgrids which need to be integrated into transport systems and the urban fabric. Demonstration urban development projects will be key in uncovering the relationship and build the components of a new NetZero precinct featuring on-demand electric shared mobility, micromobility, electrified public transport, and smart V2G orchestration management systems to take advantage of variability in renewable energy supply and stationary and mobile storage from EVs.

Linking the uptake of EVs and renewables: To safely achieve high penetration of renewable generation, energy storage systems (ESS) will be required to stabilise the grid. Electric vehicles as mobile ESS will provide this role alongside stationary ESS, although EV charging/discharging behaviour causes uncertainty in grid stability. Exploring the policies, business models and infrastructure needed to ensure a stable and balanced grid will help speed the transition to renewable energy and electrified transportation and also provide insight into the balance of mobile ESS to renewable supply.

3.1.1 Lack of understanding of the pace of the transition

Noel and Sovacool (2016) investigate the failure of Better Place (BP), which had a well-conceived business model to encourage electric vehicles. Despite substantial funds, Better Place declared bankruptcy. The paper identifies several reasons Better Place failed in Denmark, Israel, and in general. They conclude that a confluence of social, technical, political, and environmental factors precipitated the demise of BP. These factors cut across environmental attitudes and resistance to change among users, mismanagement and strategic blunders involving corporate strategy,

and higher than expected capital costs for vehicles. The authors also suggest that range anxiety may not be a functional barrier to electric vehicle adoption and may instead be an excuse given by consumers to not change their behaviour, identity, and desires regarding ownership of a vehicle.

The authors analysed articles relating to (a) the social acceptance of electric vehicles, (b) business models for electric mobility, and (c) case studies of Better Place using "interpretive flexibility." This argues that the evolutionary pathway of a novel technology such as an electric vehicle or a more refined business approach such as Better Place is a function of its technical qualities and characteristics, and equally its perception within society. In this context interpretative flexibility is of great importance as it holds that technology emerges in society as a "seamless web" (Hughes, 1986) or a "sociotechnical imbroglio" (LaToUr, 1994). This suggests that differing interpretations of the same technological device are possible in different social groups.

Sustainable development of transportation systems requires both personal willingness to change behaviour as well as consistent government support. In the absence of both these factors, market-based solutions like Better Place, despite their novelty, will face an uphill challenge. In Denmark's case society is only 'passively' greener than other societies, and because electric vehicles require active changes to behaviour or lifestyle, electric vehicle implementation in Denmark was still an uphill challenge. In Israel, general government and citizen environmental awareness did not translate to interest in electric vehicle adoption because this was not viewed as either an essential energy or national security issue. This paper supposes that range anxiety may not be a functional barrier to electric vehicle adoption and suggests we reject 'blame the battery' as an explanation for failure. Future developers of electric vehicles and its support systems should be aware of the potentially deeper connotations of range anxiety pertaining to consumer's personalities and the required governmental, societal, and personal support required for successful implementation of electric vehicles.[6]

3.1.2 Lack of integrated transport and land use planning

Sohet et al. (2020) cautions against the total commitment to bringing in electric vehicles as the problems of automobile dependence mostly remain. The authors suggest that cities should prioritise electric buses, light rail and new trackless trams along main roads with stations that have local recharge hubs for all electro mobility, especially targeting micro mobility. The integration of solar-based urban regeneration with this non-car dependent land development is a major tool for creating Net Zero Cities. The paper further notes there is great need for transformational change in Asia's transport sector, which could deliver a number of benefits for Asian cities. It describes a range of potential mechanisms now available to support such a transformation, including transport policies, infrastructure development, technological intervention, institutional arrangements, and innovative financing mechanisms among others. Key to the implementation of transformational approaches will be harnessing new and emerging technologies, including electric mobility, the use of Artificial Intelligence and online distributed ledgers, integrated land-use and transport planning, and the activation of development opportunities along corridors using integrated shared transit. The way that these types of

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[6] Note: Five years after publication range has increased to the point where price is now potentially the dominant barrier to uptake.

technologies are deployed will have a direct impact on the very functioning of cities in the coming decades.

The paper also points out that transport-related impacts from the COVID-19 pandemic have changed perceptions of acceptable pollution levels in cities and accelerated the use of active modes of transport and the role of public, or shared, transport. The recovery period will provide a unique opportunity to revise and rethink transport strategies. It is likely that capital costs of electric vehicles will be equal to internal combustion engine vehicles by 2022, with the operational costs of electric vehicles being much lower. Electrification of vehicles will not only reduce fossil fuel consumption but also create new economic opportunities as the electricity and transport sectors collaborate. These opportunities may range from creating new electric vehicle-based transit corridors with station precincts that provide charging services to a range of electric vehicles.

Li-ion batteries have revolutionised the electrification of public transit. This can be taken a step further by merging the best parts of a light rail carriage and a bus with autonomous operation and advanced stabilisation from high-speed rail to create a new and much cheaper form of urban transit technology called a 'Trackless Tram.' Not only is this technology a potential game changer for cities struggling to attract investment in traditional public transport projects, if implemented through an entrepreneurial approach in collaboration with the private sector it stands to unlock significant re-development options. Such opportunities will make public private partnerships much more viable ways of getting finance into public transport systems as it gives an urban land value base to the economics. The paper extends Transport Oriented Development to 'Transit Activated Corridors', or TACs, that are focused on a corridor of station precincts with the intention of transforming main roads policy. Such precincts need to be built in a chain along the corridor using systems that work best at a precinct scale, like solar, batteries, new small-scale water and waste systems, and new local micro-mobility electric transport systems with the attractions of high technology communications systems.

Sohet et al. (2020) investigate traffic system load management changing with the use of electric vehicles in response to how vehicle charging and range affect commuters' driving style. The authors show that vehicle charging and driving behaviours are linked and affect traffic grid efficiency as drivers choose their travel path depending on the travel time and energy costs they face.

Electric vehicles impact urban networks both when driving and charging. For the grid, the flexibility of EV charging makes it a significant actor in Demand Response mechanisms. There is therefore a need to design incentive mechanisms to foster customer engagement. A congestion game approach is used to model the performance of such a transportation system with multiple classes of vehicles – EV and ICE, applying a centralised water-filling approach to the charging price. Both temporal and energy operating costs are considered. The latter is non-separable as it depends on the global charging need of all EVs, which is scheduled in time by a centralised aggregator with nonflexible consumption at the charging location. Thus, driving and charging decisions are coupled. An adaptation of Beckmann's method proves the existence of a Wardrop Equilibrium (WE) in the considered non-separable congestion game; this WE is unique when the charging unit price is an increasing function of the global charging need.

A condition on the nonflexible load is given to guarantee the monotonicity of this function. This condition is tested on real consumption data in France and in Texas, USA. Optimal tolls are used to control this electrical transportation system and then computed to minimise an

environmental cost on a simple network topology. This closed form model is used to explore the reliability of the WE to correctly predict charging demand (and link it to price) as well its ability to minimise environmental cost.

The authors review other research that couples driving and charging behaviour. In some research only EVs are considered and their charging choices are represented in an 'extended transportation network' with no theoretical result given on the equilibrium. Other research includes ICE vehicles, but EV energy consumption is not considered in these and the charging need is assumed to be the same for all EVs. The authors' modelling in this paper appears to be more general.

The properties of WE were analysed on two real datasets of nonflexible loads, recognising that uniqueness depends on seasonal effects and electrical consumption habits. Other numerical experiments on a network example with parallel arcs illustrate two kinds of incentives sent by the Transport Network Operator and their effects on the WE. First, lowering taxes on fuel incite GV to use longer arcs – typically ring roads. Second, a toll system helps to control the proportion of GV on the shorter arc – typically crossing a city centre.

3.1.3 Lack of understanding of potential equity issues

Chung, Park and Kwon 2018) investigate equitable access to charging stations among geographical regions. Equity constraints considered for recharging location models are based on travel demand and traffic flow, and the proposed models and computational method were tested on data from an expressway network in Korea. The results show that, without equity constraints, models locate charging stations only in densely populated regions. With the proposed model, equitable distribution is achieved with a small drop in available charging in denser regions. Three types of equity constraints are developed and applied to the Korean Expressway network, consisting of 324 nodes, 880 arcs, and 104,652 (Origin-Destination (OD) pairs. Two are based on the travel demands originating from and heading to each region provided with recharging opportunities, and the other is based on the traffic-flow volume passing through each region. The authors compare the two demand-based equity constraints for the EV recharging station location problem in terms of computational efficiency and propose a heuristic algorithm for the case with the flow-based equity constraint.

Considering the public nature and the equitable distribution of facilities, the authors note that it is inappropriate to locate charging stations densely in only certain regions. When it comes to choosing locations for public service facilities, it is important to fairly distribute the benefits of facilities to all stakeholders. Equity is more greatly influenced by location changes and facility capacity than efficiency. The results show that the original arc-cover path-cover flow charging location model (AC-PC FRML) without equity constraints generates solutions in which charging stations are located only in densely populated regions. With the proposed model, equitable distribution is achieved with a small drop of traffic volume charging. When equity constraints are applied to large-scale networks and equity parameters decrease, however, the massive amount of computation time required to reach solutions is a problem. To address this issue, the authors reformulated the demand equity constraint and developed an n-phase heuristic method so that the model finds solutions within a reasonable amount of time and computation.

The authors propose several directions for further research. First, their study did not consider the capacity of recharging stations and therefore the charging time is needed for recharging EVs. Second, the paper estimates travel demand based on current traffic flows. More accurate demand forecasting is essential for implementing recharging stations. Third, the proposed n-

phase method can be further improved when combined with various local search methods such as simulated annealing or tabu metaheuristic search. Finally, the authors suggest considering the availability of charging stations outside expressway networks. In this case, we can factor in drivers' willingness to deviate from the shortest path and deToUr to recharge at those outside locations, and we can also consider equity among OD pairs instead of equity among regions.[7]

3.1.4 Lack of understanding on new business models for EVs on the grid; lack of understanding of potential of EVs to create revenue

Comodi et al. (2016) explore how local utilities can play a crucial role in building public charging station infrastructure because they manage and own the local grid. The study consisted of a payback analysis of an investment in charging stations and showed that the capacity of charging stations is a fundamental parameter to reducing the payback period and thus the investment risk. The required capacity is strongly influenced by the spread of EVs but at the same time the spread of EVs depends on the spread of charging station infrastructure.

Two ways to overcome this impasse are suggested: supporting charging station investment by a local utility by combining it with the purchase of electric vehicles, or phasing the installation of charging station infrastructure starting with locations where a high capacity is needed. The paper's most conservative scenario showed that an urban charging station infrastructure can be already profitable – without incentives – with a payback period of 4– 9 years. The context considered included the current regulatory framework, official studies on electric mobility in Italy, and official projections of energy commodities prices. Key regulatory support comes from European Directives; the most important are Directive 2009/28/CE on Electric Cars which helped pave the way for a single EV market, and Directive 2009/33/ECon for the Promotion of Clean and Energy Efficient Vehicles, which promotes clean and energy–efficient road transport vehicles in the EU by encouraging their sales. The directives cover both market incentives and standards for charging.

The study also incorporates the results of a national study of Italian consumers' willingness to buy an EV as a function of price compared to a comparable ICE vehicle. It shows that people are highly sensitive to price - nearly 40% would buy an EV if the price were comparable, less than 20% would if the price were only between €1,000-3,000, and less than 1% if the price were €10,000 more. The payback calculations also made use of estimates of average driving distance, comparative fuel and energy consumption for different kinds of light vehicles, purchase price (accounting for incentives) and projections of energy costs for all fuel types and electricity. Three EV penetration scenarios of 5%, 15%, and 30% by 2030 were considered, showing payback periods of 4-5 years in most scenarios, with higher use resulting in faster payback. The economic analysis was used by two Italian local municipalities, Osimo and Recanati, as part of a business case which led to the gradual installation of charging infrastructure.

3.1.5 Lack of clarity around optimal mix of battery sizes

Bandyopadhyay et al. (2020) investigated a multi-objective optimisation (MOO) for sizing a PV system and battery to maximise self-sufficiency and grid relief while accessing tariff incentives. The optimisation used a comprehensive optimisation model for the sizing of PV, battery, and grid converter for a microgrid system and considered multiple objectives like energy autonomy,

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[7] Note: The key contribution appears to be an advance in applied optimisation in the field of EV charging locations.

power autonomy, payback period, and capital costs. The model was applied to two residential load profiles in the Netherlands and in Texas to investigate the effect of meteorological conditions on the relative size of PV and battery. Based on the optimisation results, rules for optimal system sizing were derived to facilitate microgrid design for engineers during the initial design phase.

The main contributions of this paper compared to previous works are that it: 1) Developed a multi-objective optimisation framework to size PV system, grid converter, and battery storage capacity resulting in Pareto fronts of trade-offs between multiple objectives like lifetime capital cost, self-sufficiency, power autonomy and simple payback period; 2) Studied the effect of solar meteorological potential on optimal PV and battery sizing by comparing results at two different geographical locations: Cabauw, Netherlands, and Austin, US; 3) Investigated the effect of electricity pricing tariffs and feed-in tariffs on optimal sizing of PV and battery system; 4) Drew guidelines for selecting the optimal azimuth angle for a residential PV system; 5) Derived sizing equations and thumb rules to optimally size PV-battery-converter systems for microgrids based on solar potential and specific load profiles.

Observations obtained from the optimisation results are: 1) The local electricity tariffs in Cabauw, Netherlands, heavily incentivise energy autonomy with significant feed-in tariffs, leading to low payback periods for an initial investment. However, Austin electricity tariffs incentivise power autonomy by power-based tariffs, which lead to higher payback periods for an initial investment. 2) Solar potential of a location has a significant impact on the relative sizing of the battery capacity relative to the rated PV power. The optimal value of storage hours for Cabauw is between 2 to 4, whereas for Austin it is between 4 to 6. 3) Optimal value of the azimuth angle (Am) for the PV system is found to be the one that results in a maximum temporal match between the annual PV and load profile. 4) Rules of thumb for optimal system sizing are derived to size the battery power rating, battery capacity, PV power rating, and the grid converter rating for grid-connected microgrid application. The study can be extended to compare different battery technologies to select the most economical design. Additionally, this framework can be used to investigate the effect of intelligent power management algorithms with forecasting capability on the system sizing problem.

3.1.6 Lack of understanding of how business models link to urban development

Brandt, Wagner and Neumann (2017)[8] investigated using reserve battery capacity from EVs in parking garages to assist in grid frequency control in Germany. A business model is developed using extensive German data that assumes that there is an intermediary (in this case the parking garage operator) to aggregate and manage the vehicle to grid interactions. Results show that frequency regulation is not profitable with the then current energy prices and that charging vehicles immediately is more profitable for parking garage operators. Even if the operator installs these features to enable customers to charge their vehicles for a fee, it would be more profitable to charge batteries when the vehicles enter the garage instead of delaying charging for frequency regulation. This result held across different scenarios. The paper concludes that the relationship between electric vehicles and the integration of renewable energy sources

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[8] Note: The input data are quite old (2014) and the increased penetration of renewables may have a strong effect on these conclusions.

requires a closer look at the associated business models to derive robust economic and policy implications even though the schemes are technically feasible.

The authors cite considerable earlier work on vehicle-grid integration (VGI), noting that the studies are deficient in real world business models and do not adequately cover parking garages, which they adopt as their focus. Their analysis begins with how well VGI aligns with the general business interests of parking garage operators from four perspectives: product, customer interface, infrastructure management, and financial aspects. Due to a lack of real-world data, simulation methods are used to understand the profitability of the business models proposed by using data from the energy and frequency regulation markets in Germany, parking garage occupancy, and states of electric vehicle charge during the day - the latter being crucial as it determines the potential for regulation. Depending on vehicle type, the state of charge varied between 60% and 85% during the day. On average, vehicles were driven 4% of the day, charged 11% of the day, parked 29% of the day, and idle the rest of the time.

The findings have direct implications for policy. The then current market environment does not allow EVs to provide frequency regulation, but results show that the lack of an appropriate market is not the critical issue for VGI feasibility. Even if a market for stochastic reserves existed, it would require substantially higher market prices for regulation energy to result in a viable business model. The authors suggest that the potential of EV aggregators to provide ancillary services as described in the literature may be exaggerated, and the widespread adoption of electric mobility may become a more critical issue for the power grid than is currently expected.

3.1.7 Poor adaptation of public transport networks to Battery Electric Buses (BEB)

Wei et al. (2018), published in the Journal of Transport Geography, identified a method of minimising the cost associated with vehicle procurement and charging station allocation while maintaining existing bus routes and schedules. This research is particularly important for implementing Battery Electric Buses (BEB) in urban areas by helping transport agencies to make critical decisions regarding the integration of BEB into their fleet. Traditional bus routes are based on transport demand instead of the location of fuelling/recharging stations. The location of charging stations along BEB routes presents a barrier for the uptake of EVs as suitable locations for required charging infrastructure do not always correlate to the areas of transport demand.

The paper's contribution is to develop a method to optimise deployment of BEBs and associated charging infrastructure while explicitly accounting for the spatial and temporal constraints imposed by vehicle configuration, charging station capacity (both on-route and in-depot), as well as transit vehicle schedules. The method was applied in a study of the potential adoption of a BEB fleet operated by the Utah Transit Authority. A key conclusion from the study was that the number of BEBs introduced to the existing network demonstrates a logarithmic-like pattern of diminishing returns with the number of en-route charging stations required. This implies that initially charging stations and BEBs can be selected at highly dense service locations such as the Central Business District, where several routes cover smaller geographical areas and are passing a main transit hub multiple times a day. As the network expands, routes are longer and there need to be comparatively more recharging stations per route.

The BEB network expansion pattern has important policy implications. To begin, a sizeable portion (e.g., 20%) of diesel or CNG buses can be replaced with BEBs with only a limited number of en-route charging stations needed (if deployed properly). The number of en-route charging stations required for serving the same number of BEBs in denser areas of the transit network is

significantly less than in low density service regions, which makes BEBs a favourable choice for locations with larger population and job density that are serviced by a high-density transit network. The model also enables comparison of short-term (i.e., 15% of bus fleet is replaced with BEBs), mid-term (i.e., 50% of bus fleet is replaced with BEBs), and long-term (i.e., the entire bus fleet is replaced with BEBs) investment planning and find the investment tipping point.

The authors suggest the modelling method could be extended to incorporate other transit agency prioritised goals such as maximising fuel efficiency, lowering environmental impact, and air quality improvement. Integrating various and competing goals into the model will in future allow transit agencies to address their specific and prioritised needs. The model currently only accounts for the capital investment of the BEB system due to the data available but it could also account for operational cost. Other factors the authors may consider in follow on research include the possibility of connecting to the power grid, and land ownership and space issues. Note this model could be a useful planning tool for Australian bus operators.

3.1.8 Lack of clarity on behavioural aspects of EV use

He, Yin and Zhou (2015) [9] explore how to optimally locate public charging stations (within a set budget) for electric vehicles on a road network, taking into account drivers' spontaneous adjustments and interactions of travel and recharging decisions. The proposed approach captures the interdependency of different trips conducted by the same driver by examining the complete journey of the driver. Given the limited driving range and recharging needs of battery electric vehicles, drivers of electric vehicles are assumed to simultaneously determine journey paths and recharging plans to minimise their travel and recharging time and guarantee not running out of charge before completing their journeys.

The paper proposes a ToUr-based, mathematically tractable BEV network equilibrium model to capture drivers' reaction to the deployment of charging stations in their route and recharging decisions given the locations and types of public charging stations. The authors define network equilibrium conditions and formulate them into a mathematical program. An iterative procedure is proposed to solve the program to find the equilibrium pattern. Based on the proposed ToUr-based equilibrium framework, the problem of optimally locating public charging stations within a budget limit is formulated as a bi-level mathematical program, which is then solved by a genetic algorithm. The model ignores the possible congestion occurring at public charging stations. ToUr-based network equilibrium models assign traffic demand based on the analysis of a complete ToUr, which may consist of several trips in a predetermined order and captures the connection of different trips conducted by the same traveller, which is significant for BEVs.

Interestingly, while modelled examples assume that all vehicles are BEVs, conventional ICE vehicles can be modelled as part of the mix as well. It also accommodates drivers with different risk appetites. For example, risk-averse drivers may prefer a larger 'buffer' of charge and therefore recharge more frequently. The model is claimed to have two advantages: First, to accurately track the state of charge of the battery as the initial state of charge for a particular trip is always related to its previous trips. Second, it considers the duration times that BEV drivers spend at various destinations (i.e., intermediate stops) in a ToUr that may be utilised for recharging.

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[9] Note: The paper is quite old and EVs have much higher ranges now. While the models will hold for longer driving ranges, drivers will eventually not be concerned with range.

A numerical example is presented to demonstrate that the model can prescribe optimal locations and types of public charging stations to be deployed and predict their utilisation and the composition of their customers. The latter is useful for detailed operation planning of public charging stations. In addition, travellers' recharging information, including average recharging frequency, amount, and time, can be used to estimate the extent of inconvenience for drivers to fulfill the recharging needs of BEVs, which is an important reference for potential BEV adopters. The model was applied to Sioux Falls in the US. Further work will extend the model to include finite capacity at charging facilities.

3.2 Barrier: Edge of grid

Edge of grid refers to the outer reaches of large, centralised grids that are traditionally based on the assumption of a one-way flow of electricity to a small number of customers. Small country towns are usually the feature of edge-of-grid. This area of the grid has poor reliability, is typically poorly serviced, and as it transitions to local energy generation with a microgrid attached to the main grid and storage options the role of EVs needs to be considered. Key barriers to consider are a lack of understanding of new edge of grid business models, a lack of consensus on how to control emerging microgrids, and the problem of localised low generation and high EV battery demand.

Understanding edge of grid business models is essential for building investment in the expanding and fringe areas of microgrids (MGs). The shift to a bidirectional grid from a one-way grid with large centralised generation requires upgrades to edge-of-grid operations. This will require developing new business models that allow customers to access localised generation and storage and investment in upgrades to grid infrastructure that can include V2G. It is important to understand how business models can affect the structure of MGs from a socio-economic approach as it will affect customer access to this localised infrastructure. There is a need for a systematic approach centring on users' needs and habits, assessment of efficiency at various scales of V2G, associated services, and the power grid (Sechilariu *et al.*, 2019).

A decentralised grid creates opportunities for microgrids connected to the main grid especially in industrial parks and edge-of-grid locations and there are issues to resolve around the extent of storage in the microgrid to ensure grid dependence. However, a lack of consensus on how to control emerging microgrids is a barrier to deploying networks that provide customers with competitive energy prices and greater reliability. Duverger et al. (2018) developed a model for minimising operational costs in a microgrid. Classification of microgrids is important to optimise management of energy sources, control strategies, protection schemes and communication networks. Various tools can be used, including a Hybrid Optimisation of Multiple Energy Resources (HOMER) and particle swarm optimisation algorithm (Shaikh *et al.*, 2021).

Mitigating the disparity of localised low generation and high EV battery demand is coupled with developing business models involving edge-of-grid and remote grid stakeholders. As grids change, the options include whether to create stand-alone power with solar, batteries, and back-up power instead of microgrids connected to the main grid. These stand-alone systems currently use diesel, so a question to resolve is whether EV-based storage could meet the extra demand while providing the same resilience as back up diesel. Rawat et al. (2019) show that charging/discharging strategies for both microgrid types can be modelled to optimise microgrid operational costs. Uncontrolled charging of EVs results in higher microgrid operational costs, charging during light grid load or when renewables are contributing decreases costs by a quarter,

and allowing charging and discharging halves costs. V2G charging offers load shaving, evens the load profile, and reduces input from the mains grid.

Research opportunities

Viability of hydrogen as a V2G Technology: Examining the potential for green hydrogen-powered microgrids, especially for heavy vehicles used in mining and freight (this also applies to remote grids).

Live data collection and exchange for microgrid performance: Developing predictive modelling to forecast microgrid reliability and costs using live traffic, battery, and electrical load data from Australian microgrid projects as learning sets to develop a tool to identify precincts where microgrids are viable.

Business models and microgrid growth: Investigating how business models and related incentives can motivate stakeholders (vehicle owners, energy providers, developers and government) to support the growth of microgrids.

3.2.1 Lack of understanding of new edge-of-grid business models

Sechilariu et al. (2019) describe an intelligent infrastructure dedicated to recharging EVs in an urban area in France where the charging station uses a photovoltaic microgrid. The system facilitates interactions between the intelligent infrastructure, the public power distribution network, the users of EVs, and the surrounding buildings. It is implemented in an experimental charging station (Electromobility Living Lab) integrated with a PV-based microgrid and able to interact with the public power distribution network via smart grid messages, and with the EV users and the surrounding buildings via a dedicated human machine interface. The lab supports nine PV-shaded parking spaces, some 30kW of PV, public grid connection, load emulators, battery and supercapacitor storage, and power electronics. This energy system is able to manage optimised power flows, supporting V2G-discharge of EV batteries into the public grid, V2H-discharge of EV batteries into the building, and intelligent infrastructure-to-home (I2H) electricity supply.

An experiment with a multidisciplinary framework of electromobility was devised that provides starting points for the design of intelligent bidirectional V2G charging infrastructure and an urban deployment methodology based on a multi-criteria analysis from a social acceptance survey. It was sited within appropriate urban areas and accounted for societal attitudes and sustainability. The experiment investigates an incremental innovation compared to existing PV-shaded car parking, which, while producing clean energy, is passive, with energy rarely consumed locally or rarely accounting for users and their environment.

The study claims a number of contributions: coupling renewable energy production within an urban microgrid with an optimised model of energy management; defining an intelligent infrastructure dedicated to recharging EVs in an urban area with a charging station powered by a PV-based microgrid; and providing key elements to encourage stakeholders to develop intelligent infrastructure accounting for social, urban planning, and sustainability goals. It also served to highlight multidisciplinary research that demonstrates the need of a systemic approach to centre on user demand and needs to assess efficiency at various scales of systems associated services and power grid, and used a multi-criteria analysis framework leading to a technical–economic–environmental evaluation methodology for intelligent infrastructure combined with a case study in Compiègne (France)

The study concludes by expressing the need for a systemic approach to centre on users' needs and habits, assess efficiency at various scales of V2G, associated services, and the power grid. The multi-criteria methodology also identifies 'best fit' locations for PV-based EV charging that takes into account employment data, population, car parking amenities, locations and characteristics of the car parks, locations of public services, points of interest, main routes and so on.

3.2.2 Lack of consensus on how to control emerging micro-grids

Shaikh et al. (2021)[10] aims to provide a comprehensive review of microgrid-adopted technologies, control methods, existing applications, software tools, and AI techniques. The review also outlines the techno-enviro-economic assessment and global investment in development and deployment of microgrid projects. It makes few conclusions but is valuable as it outlines all actors and technology components, and classifies grids and microgrids clearly. Both renewable and non-renewable energy sources are discussed and analysed. Similarly, several control strategies, protection schemes, and communication networks used for microgrids are defined to provide distinct perspectives for optimal and on-time projects. During the review analysis different software tools and techniques are applied across the different microgrid implementations. The most frequently used was a hybrid optimisation model for electric renewables (HOMER) Pro and a particle swarm optimisation algorithm.

Microgrid configurations were categorized as DC-coupled, AC-coupled, and Hybrid AC/DC. Energy sources and storage considered were PVs, wind, micro-hydro, biomass, geothermal, diesel and natural gas, fuel cells, and lead-acid and lithium batteries. Control methods and structures used were centralised, decentralised, master-salve, multi-agent, distributed autonomous, two-level hierarchical, and three-level hierarchical. The paper also characterised control parameters as current variation, voltage stability, primary frequency regulation, and power management. Microgrids were classified according to location and application as campus/institutional, military, residential, agricultural, remote and rural, hospital, and EV. Software tools observed for designing microgrids were HOMER Pro (most used), HOGA, HYBRID 2, HYBRIDS, MATLAB, PSCAD and RET Screen. Forecasting approaches using AI included genetic algorithms, particle swarm optimisation, ant colony optimisation, artificial bee colony, and cuckoo search.

The authors also review the electricity generation and deficit in different regions, highlighting areas where especially high populations do not have access to electricity (e.g., South Sudan – 99%). The reason for this analysis is not given but may be to highlight areas where microgrids would be useful. Total global installed capacity for renewable sources is calculated at 2588GW, including 627GW from PV, along with the global investment of USD 316.7 Billion (2019) in clean energy sources. Calculations were made on the least-levelised cost of energy for on-grid and off-grid hybrid systems using HOMER Pro and found to be $0.072 and $0.145/kWh, respectively.

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[10] Note: The paper is impressively comprehensive, covering all types of microgrids, energy sources and control and planning algorithms and software tools – which is useful. The conclusions are insubstantial apart from an energy cost comparison of off and on-grid systems. The language is quite difficult to understand.

3.3 Barrier: Remote grids

Remote grids refer to electricity grids in locations that, due to distance, cannot connect to the main grid, or micro-grids that have chosen to disconnect from the main grid. These grids are usually for mining camps and their associated mining activities, for Indigenous settlements of various sizes, some ToUrist sites, and other remote communities. Consequently, they are of high importance in Australia. Key issues include a lack of understanding of required EV scale for remote grids as to replace current generation and back-up options (typically fossil-fuel diesel or gas generators) it must be clear what critical mass of EVs and stationary storage will be needed to ensure supply reliability. Remote grids will also likely serve as recharge stations for EVs travelling cross-country, requiring high capacity and infrequently used PV charging and high-capacity battery storage to be ready for transients. Haupt et al. (2020) look at charging strategies for microgrids containing mixtures of EV and stationary batteries.

Further, set-up costs for remote microgrids are important to remote communities who need to establish a self-contained electricity network including generation and storage as well as back-up. This will be usually more expensive than denser, city-based systems, however remote grids will have greater spread and variety in the use of PV, the community's batteries, and EV storage, which may make business cases more complex but less expensive than present systems. Demonstrations are needed to show how best to proceed. Zia, Elbouchikhi and Benbouzid (2019) developed economic models for operational planning of such systems, while Shaikh et al. (2021) provide some cost comparisons of diesel and gas microgrids versus solar and wind. Related to this is dependence on vehicle location: Daytime charging will require EVs to be located adjacent to PV generation unless costly infrastructure from PV to EV is installed. Photo voltaic generation will be established next to the demand area, and recharge sites should be considered for installation in depots for V2G opportunities from idle transport vehicles. Solving such siting issues will require demonstrations. Badawy and Sozer (2017) describe a relevant small-scale demonstration.

Remote areas are often high sunshine environments with plenty of space for PV collection. In the future remote mining areas are likely to be required to have substantial areas of PV to enable hydrogen to be created for mineral processing. It is therefore important to assess the potential for the use of hydrogen and V2G potential to manage the power supply. These grids will need to be carefully integrated with large industrial processes, and significant storage may be needed for grid stability. The role of heavy trucks with very large batteries will need to be part of these considerations. No significant relevant literature was found in this area.

Research Opportunities

Electric vehicles as energy storage in remote grids: Models for understanding the role of EVs in augmenting stationary storage for remote microgrids.

Design tools for Australian remote grids: Tools which allow remote communities, or jurisdictions with remote communities, to calculate the set-up costs, running costs, and reliability of renewable powered microgrids and compare these with fossil fuel equivalents while factoring in EVs as part of the energy storage solution.

Live data collection and exchange for stand-alone microgrid performance: Developing predictive modelling to forecast microgrid reliability and costs using live traffic, battery, and electrical load data from Australian microgrid projects as learning sets to develop a tool to identify precincts where stand-alone microgrids are viable.

Viability of hydrogen as a V2G technology: Examining the potential for green hydrogen-powered microgrids, especially for heavy vehicles used in mining and freight.

3.3.1 Lack of understanding of required EV scale for remote grids

Zia, Elbouchikhi and Benbouzid (2019) consider a grid-connected DC microgrid which consists of a PV system and a Li-ion battery. With advances in power electronic devices, the increasing use of DC loads, DC renewable generation sources and battery storage systems, and no reactive power and frequency stability issues, DC microgrids are increasingly gaining attention in both academia and industry. Incentives are considered which encourage customers to shift load during scheduled grid-tie line maintenance. Direct current microgrids' optimal operation requires battery degradation cost modelling and demand response incentives for the active participation of consumers to be addressed in detail. Therefore, a practical degradation cost model for a Li-ion battery was developed to optimise battery scheduling and achieve realistic operational cost. Apart from energy price, scheduled islanding responsive demand response incentives were also introduced to encourage customers to shift load during scheduled grid-tie line maintenance.

As optimal operation of DC microgrids cannot be achieved without considering nodal voltages and system losses, network constraints were also included in the proposed model. Results may aid in DC microgrid adoption planning as they replace traditional AC grids in the future. Simulation results confirm that the integration of battery degradation cost and islanding responsive demand response incentives in DC microgrid applications will significantly influence the operating cost.

Key contributions of this paper are: Regression models to determine temperature and depth of discharge (DOD) effects on cycle life and energy capacity degradation of a Li-ion battery; a practical battery degradation cost (BDC) model of Li-ion battery using the developed regression models; a practical levelised cost of energy (LCOE) of a PV system for hot and cold climate regions using real temperature and irradiance data; and introduction of incentive-based demand response (IDR) to encourage customers to change their consumption patterns during normal operation. Additional contributions are an islanding responsive IDR proposed to encourage customers to shift load from scheduled islanding periods to normal operation periods; and power flow of a scalable DC MG system also included in the optimisation model to regulate bus voltages and compute system losses.

The paper concludes that introducing islanding responsive demand response incentives and increasing the value of the shifted load demand and the demand response shift duration greatly reduces the operating cost of the DC microgrid. Finally, temperature effects on the operating cost of the DC microgrid without a photovoltaic system were also analysed. Costs were higher in cold climate regions due to increased power fading of a Li-ion battery at low temperature. The results confirmed that the integration of battery degradation cost and islanding responsive demand response incentives in DC microgrid applications significantly influence the operating cost.

Haupt et al. (2020) suggest that "The influence of electric vehicle charging strategies on the sizing of electrical energy storage systems in charging hub microgrids" is motivated by needing to understand the economic feasibility of microgrids (MGs). The authors establish that energy storage systems (ESS) are essential to charging hub microgrids (CHMGs) and currently largely stationary, although with the penetration of EVs there will need to be a mix of stationary ESS and mobile EV ESS. This paper claims that current research lacks evidence and guidance on

charging strategy influences, hence a method has been generated that uses mixed-integer linear programming modelling for scheduling decisions of various ESS capacities and scenario analyses for EV charging and ESS costs. The model considers both ESS and EV constraints as well as CHMG energy balance and grid connection constraints. The case of a large (144 charging ports) projected CHMG near Augsburg, Germany, is used to demonstrate the methods developed and compares different charging strategies.

The authors point out that planning and sizing of stationary ESS for CHMGs differs from those of other types of MGs: EVs plugged into the microgrid serve first as loads, and then as potential ESS. CHMGs might have the capacity for more than a hundred EVs. Aggregating these EVs lets them appear as one virtual storage unit. However, from a microgrid planning perspective, the volatility of the virtual storage poses new challenges such as its time varying capacity.

The capacity variation is due to the differing arrival and departure times of the EVs causing a fluctuating number of EVs plugged to the MG at any particular time, the diverse battery characteristics of EVs, and the specific charging strategy, which can be one of immediate charging (i.e., the MG lets the EVs instantaneously recharge as fast as possible whenever they plug into the charging port), controlled charging (i.e., the MG controls the charging rate anywhere between zero and the maximum), and bidirectional charging, whereby the microgrid controls both the charging rate and the discharging rate to the microgrid.

Key findings are that charging hub microgrids are gaining increasing importance in electric mobility; stationary electrical energy storage is a key component in charging hub microgrids; sizing storage is practically relevant and non-trivial; the optimal energy storage size is sensitive to the mix of electric vehicles' charging strategies; and, the results of the case study indicate bidirectional charging may not pay off, however controlled charging is important economically and this is the approach recommended by the authors. In all cases, operational costs decrease with larger installed ESS, and if battery prices drop below 300 EURO/kWH the CHMG is economically feasible for all charging strategies. Finally, the required storage is highly sensitive to the number of EVs charging at the station. The stationary storage capacity soars if more than 65% of the EVs begin charging and falls drastically if the load factor is reduced.

3.3.2 Dependence on Vehicle Location

Badawy and Sozer (2017) present an optimal technique for power flow in a PV-battery powered EV charging station designed to support fast charging. The system includes PV, battery, and AC to DC input from the electricity grid, with DC loads including the electric vehicle. System management includes two stages for optimisation: offline heuristic optimisation using particle swarm optimisation, and online dynamic programming (DP) in conjunction with a centralised controller. The first processes data to forecast the next 24-hour period for accurate grid tariff forecasting and to assign an optimal state of charge to EV batteries every hour. This is calculated by the second process, DP. The model considers dynamic grid tariffs and battery degradation cost. By iterating the experiment, the system converged to a minimum (optimal) price for electricity.

The core of the paper is a power flow optimisation carried out to minimise the system running cost while continuously supplying the desired loads. Factors considered in the model include grid running cost and battery degradation cost, accounting for the impact of temperature, state of charge, and depth of charge. Arguments are given for using particle swarm optimisation for its high accuracy but keeping it offline due to the high computational cost.

For online optimisation and error compensation dynamic programming is used for its dynamic ability and the non-linear nature of the problem. The reduction in the system running cost is achieved by means of peak shaving, using forecasted data alongside with the healthy operation of the battery pack in the proposed system in order to extend its lifetime. Together, these optimisation systems comprise the system control structure.

The optimisation is validated using two simulation case studies and a 1kW test system. The simulations use two different power load forecasts over a 24-hour period with similar PV generation. In both cases peak load is shaved successfully, and the optimisation shows 20-40% extension in battery life over methods which do not account for battery degradation and only use grid tariff.

Simulated loads were input to the test system and optimal power flow scheduling was applied, showing results comparable to the ideal simulated scenario. The presented data indicate that the power converters along with the control structure applied are capable of tracking the optimal power flow conditions through the applied time interval. The PV converters also successfully tracked the maximum power point under rapid variations in the insolation level. Last, the experimental system demonstrated stability under different and varying operating conditions.

The paper concludes that it has met its broad objective to help the penetration of PV/battery systems into the grid and to support the growing need for fast EVs charging rates. It achieves this by continuously minimising the system running cost while considering both the dynamic grid tariffs and the battery degradation cost.

4. Social Science Research for EVs

Much of the debate about EVs revolves around abstract, technical calculations and simplistic assumptions about cost and benefit. Tariffs, taxes, and other incentives are important in shaping decisions, but the user experience and its relationship to everyday practices, the built environment, and urban planning is too often overlooked.

We build our cities and they build us. Acquiring, managing, and driving an EV involves a complex set of interactions between the person behind the wheel and the technology around them. Understanding what is involved is crucial to the uptake of EVs and especially to maximising the potential social, economic, and environmental benefits of EVs.

Encouraging greater uptake of EVs will be important to a variety of actors, car manufacturers, and network businesses. Yet many of the problems of our current car-centric system are not addressed by EVs (Henderson, 2020). Electric vehicles will still produce tyre and brake particulates and will still cause deaths and injuries - road traffic deaths are currently the number one cause of deaths among children and young people, causing around 1.35 million deaths every year (WHO, 2019). Another 20-50 million people are seriously injured in traffic accidents each year, often resulting in lifelong disabilities. These deaths and injuries occur disproportionately amongst minority populations where such categories are recorded, such as in the USA (Adams, 2021). Conservative approaches in which EVs are used primarily to reduce tailpipe emissions and reliance on fossil fuels - enabling transport to continue otherwise on a 'business as usual' basis - are not enough (Milton, 2021). We need what Milton describes as a 'progressive vision' for EVs: one centred on shared and intermodal electric mobility (Milton, 2021). As NSW Minister for Planning Rob Stokes recently argued –

> "[EVs] still perpetuate physical inactivity and propagate sedentary lifestyles. Of course, private vehicles are wonderful servants, but they make terrible masters. Changing from a polluting master to a more efficient master does not alter our growing dependence on – some might say enslavement to – private motor vehicles." (cited in Rabe, 2021).

In urban areas where other options are more readily available, EVs will need to be part of a much wider transformation that includes changes to the built environment and urban governance as well as tax and fiscal settings. The progressive vision for EVs sees new ways of creating value from consumers' devices and practices through managed charging, sharing models, and more efficient vehicle asset management, as well as better integration with walking, cycling, and public transport, especially electric micromobility (e-bikes; e-scooters). The potential for new ecosystems of shared value between businesses and consumers also aligns with the RACE for 2030 E1 Opportunity Assessment on Trust, which stresses the importance of dialogical, transparent and responsible business practices rather than those which simply assume value is created by the EV industry. This must include the ways we understand the industry and its relationships to consumers, as well as the way in which governments and other actors engage with and shape the environment in which EVs operate.

This opportunity assessment has revealed a significant shortage of social science research on EVs and its interaction with the grid. There is an urgent need to undertake studies to better understand how to maximise the benefits for users and the wider community. We simply do not know enough about:

- how early adopter user demographics translate into mass market development.
- who the potential mainstream adopters (early majority and late majority) are and which factors would influence their uptake.
- emerging public and private charging norms (responsibilities as an EV user) and social dimensions of managing charging.
- how the social and economic dimensions of transport use and planning will influence the valuation of EVs as distributed energy resources.
- charging infrastructure placement planning, including public chargers, as well as regulatory and other barriers to the installation of private chargers (e.g., in apartment buildings, fleets, and workplaces).
- how EV use influences other travel behaviour, especially in relation to active and public transport and to shifts in mobility during COVID-19 restrictions.
- how the development of EV infrastructure can encourage sustainable mobilities, including car sharing, ride sharing, and active transport.

- the conditions under which commuters - in a post-COVID-19 environment - will charge at their workplaces, and the role of charging infrastructure, workplace culture, and incentives in shaping daytime charging.

- how other forms of electrified mobility (e-bikes, e-scooters etc) are being used and the strategies through which greater use could be encouraged to facilitate the wider transport changes necessary for sustainable mobility.

4.1 User demographics, purchasing decisions and mass-market adoption

Pioneering/early adopter EV owners are not representative

Currently there is a gap in our understanding of mainstream EV adopters (early majority and late majority), including who they are and what factors would influence their uptake. Usage cases are largely extrapolated from early adopters (Daramy-Williams, Anable and Grant-Muller, 2019), who are not representative of the wider population (much more likely to be male, older, engineer of some kind). Studies that have considered mainstream adopters have found that pioneer PEV owners compared to mainstream PEV owners have higher levels of income, education, recharge access, prioritise renewable energy for charging five times more than the wider population, and have higher engagement with environmental and tech-oriented lifestyles (Axsen, Goldberg and Bailey, 2016). Axsen, Langman and Goldberg (2017) did look at mainstream consumer perceptions of EVs in Canada, finding that they lacked knowledge but were positively inclined once gaining an understanding.
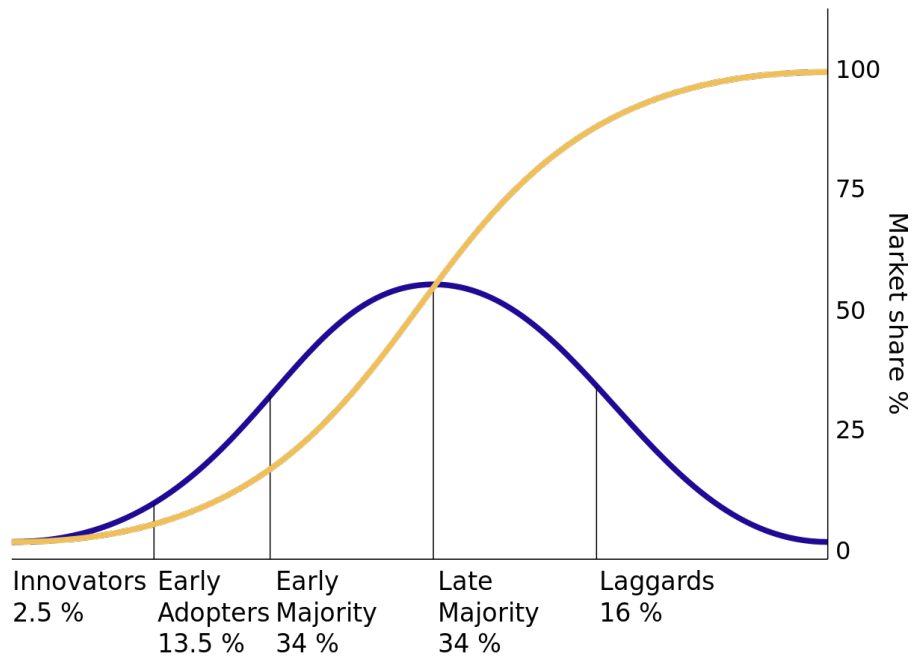
Figure 22. Innovation adoption curve (see Rogers, 1995, ref in comments)

The cheapest EV model in Australia is the MG ZS EV priced at $43,990 which has been available since late 2020. The second-hand EV market is so far virtually non-existent. Nevertheless, when cheaper EV models do become available and second-hand EVs enter the market, we can expect that "a younger and more diverse user group may emerge with different attitudes, routines, habits and behaviours, socio-economic statuses or spatial distribution" (Alkhalisi, 2020).

There is poor understanding of how early adopter user demographics translate into mass market development.

All major technical studies into the grid-EV interface have relied on early adopters. This reliance severely hampers the external validity of studies, their relevance to Australian EV users, and its bearing on 'the problem' of exacerbating the duck curve articulated above.

The limited research available suggests demographics of EV purchasers are "typically middle-aged, well-educated, affluent men" (Dütschke *et al*., 2012; Campbell *et al*., 2014; Plötz *et al.,* 2014, Hardman *et al.,* 2018). Australian early adopters of EVs reflect this, with the additional qualification that they are 'pro-environmental motorists' (Broadbent, Metternicht and Drozdzewski, 2019). Early adopters tend to be both enthusiastic about technology and its capacity to solve environmental issues. "EV buyers are more heavily concentrated in the 40–69 year age group than ICE consumers" ((Alkhalisi, 2020, citing Knight *et al*., 2015).

In a Nordic demographic study, Chen et al., (2020) found that "Younger males with higher income, more children, and experience with EVs are related to potential EV adoption." Nevertheless, Anfinsen, Lagesen and Ryghaug (2019) looked at EV user representation in Norway through a gender studies lens and found that " ... EVs seem to appeal equally to both women and men, framing their enthusiasm within differently gendered narratives."

Purchasing decisions are contextual, however trial drives improve perception of EVs

Purchasing decisions are driven by different motivations and research tends towards narrow, jurisdiction-specific studies. There is a gap in understanding purchasing decisions that may be relevant in the Australian context given the particularities of our cultural and political environment (e.g., EV tax in Victoria). Lin and Wu (2018) considered demographic factors influencing purchase in the four largest cities in China, finding that marriage and high concerns about smog increased purchase intentions, with education, income, and car ownership having no significant effect.

Schneider et al. (2014) use a diffusion of innovation model that stresses that increased information about, and experience with, electric vehicles positively influence their evaluation by prospective consumers. An important finding is that 'trialability' - literally the ability to trial an EV - is particularly important in developing positive associations with EVs for both prospective buyers and other drivers.

Fleet manager studies

Perceptions of EVs are situated in social categories such as class, income, and values, while also being contingent on wider issues such as pollution. More sociological studies need to be undertaken, particularly in the Australian context, to better understand who is using EVs and the factors influencing use by both early and mainstream adopters. This is true both of private buyers and fleet managers. The RACE CRC is ideally placed to help understand how perceptions of the value of EVs are shaped in both individual household and large organisational contexts.

4.2 Charging behaviour and social acceptance

Charging norms and subversive charger uses

Charging norms are still emerging, and early charger behaviour studies are challenging expectations of use. Currently EV charging is associated with a range of practices, some of which can be considered 'subversive.' Subversive uses include PHEV drivers running the ICE engine to recharge using the re-generative braking system (Kester *et al.*, 2020) and charging station hogging (Wolbertus and van den Hoed, 2018).

Analysis of Australian EV charging practices - including public, work-based, and at-home charging is limited, as is our understanding of the charging norms for mainstream adopters. For an understanding of the diversity of EV charging practices, the following studies can be considered:

- Many studies use cluster analysis of charging data to infer patterns of behaviour. However, without qualitative analysis of user demographics and related issues, Helmus, Lees and van den Hoed (2020) analysed 4.9 million charging transactions in the Netherlands between 2017-2019. They clustered the charging sessions, finding that "none of the user types display solely stereotypical behaviours as the range of behaviours is more varied and more subtle." Furthermore, this study only considered Level 2 public charging and the authors noted that 80-90% of EVs in the Netherlands are company cars and therefore likely biased towards drivers with higher income, higher education, and accumulating larger mileage.

- Kuby (2019) examined early AFV-adopter use of charging infrastructure when severely restrained in the choice of transport. The work uses US data to conclude that AFV users tend to habitually refuel "on their way, mid-trip, and near work", while charging less often near home.

- Morrissey, Weldon and O'Mahony (2016) analysed data from all public fast-charging stations in Ireland to find that EV users prefer to charge from home at peak demand times (evening) and are more likely to use fast charging at other times, preferably at car park locations for charging. There are 711 charge points across Ireland, 83 of which were fast chargers (43/50kW DC), and 609 standard charge points (22kW AC). A large proportion of charging events start at 9am and charging practices remain relatively stable until 7pm. They also observed a relatively even split between charging at petrol stations, car parks, multimodal points, and street and household.

  Sun, Yamamoto and Morikawa (2016) looked at how users choose fast-charging stations in Japan in a 2-year field study, finding that ~50% of charging events have over half the battery level when stopping, ~26% had 3/8ths, ~23% had ¼ left. Commercial users were much less willing to deToUr (0.5km). Sun, Yamamoto and Morikawa (2015) found that EV drivers tended to recharge earlier than necessary (by 14-19km) considering the number of charging stations along their route, likely due to range anxiety.

- Franke and Krems (2013) examined data from 79 EV users in Germany to characterise their charging behaviour, finding that "On average, users charged their EV three times per week, drove 38 km per day, and they typically had a large surplus of energy remaining upon recharging."

- Lee et al. (2020) explored charging patterns given a mix of charging infrastructure in California, finding that female and older plug-in EV owners prefer home over non-home charging.

- Wolbertus and Van den Hoed (2019) in the Netherlands found a preference to using fast versus on-street home charging. The study found that people prefer on-street home park- and-charge rather than fast charging.

- Caperello, Kurani and TyreeHageman (2013) look at how etiquette influences EV charging behaviour in California based on transcripts of interviews of 28 driving households. "Themes about etiquette emerged within two types of away from home charging. First, public chargers (available to any PEV driver) were the sites of situations in which drivers perceived a lack of rules or conflicts between different systems of rules; both were described as inhibiting use of public chargers. Second, workplace charging (typically available only to employees of the entity where the charger is located) adds an additional layer of rules and possibly resources that may either inhibit or encourage PEV charging by employees. As PEV markets and charger networks grow, charging will be shaped by additional systems of rules and regulations (e.g., those governing financial transactions). Our results suggest that absent efforts to help PEV drivers develop, learn, and practice the new rules, they may create as much uncertainty as guidance."

Research opportunities

There are significant research opportunities in how subversive uses of public charging can be combated. These uses include different kinds of 'charger hogging' as well as ICE interference. Different kinds of subversive use might affect assumptions around the EV interface with the grid.

Social dimensions of managed charging

Smart charging could take place under various arrangements, considering needs of households, local government, and businesses. How EV consumers and prospective buyers perceive these arrangements is a gap in the literature, with only a few studies conducted outside of Australia.

Managed/smart charging technologies and arrangements are widely considered essential in ensuring grid stability with increased EV uptake. Managed/smart charging requires consumer acceptance, yet already issues of inconvenience, distrust, confusion and fear are associated with these technologies (Sovacool, Axsen and Kempton, 2017). Sovacool et al. (2017) argue that "alterations in charging could interfere with consumers' driving behavior or lifestyle, present a threat in the case of emergency, or increase the proportion of gasoline-powered miles relative to electricity-powered miles in the case of PHEVs."

"Moral values can act as drivers and barriers for consumer and citizen acceptance of smart grid technologies ... environmental sustainability and security of supply positively influence smart grid acceptance. On the other hand, concerns about privacy, security, or health negatively impact their acceptance." (Milchram *et al.*, 2018)

Survey analysis in the UK and Germany has emphasised the importance of the social dimensions of smart charging. Delmonte et al.'s (2020) UK study of perceptions of smart charging conducted 60 semi-structured interviews with actual and potential PEV users. They found that user-managed charging based on ToU tariffs was preferred over supplier-managed charging. Furthermore, they found perceived personal control for user-managed charging and lower perceived risk that vehicle would not be fully charged when needed.

Will and Schuller's (2016) German survey-based analysis of 237 early adopters showed that key motivations for smart charging acceptance are contributing to grid stability and integration of renewable energy sources.

Sovacool et al. (2017) also reported on a Canada-based survey which "found that 24% of new vehicle buying respondents believed that a VGI program would be an "invasion of privacy", and 39% indicated that a VGI program might "take control away from me in a way that I would not like." Interviews with Canadian new vehicle buyers found that most mainstream participants had a difficult time understanding the concept of vehicle-to-grid, including the notion that timing of PEV charging could improve grid efficiency or reduce environmental impact." Battery degradation is also a concern among 'PEV Pioneers.'

Research opportunities

More research is necessary to understand emerging charging norms and how these influence and interact with other aspects of user behaviour, including managed charging.

4.3 Infrastructure planning and sustainable mobilities

Charging infrastructure

EV charging station planning lacks a multidisciplinary perspective. There are many variables that may impact which placement is optimal when, why, and for whom.

Charger planning in the literature tends to take an 'optimal' location approach – 'optimal' in terms of power networks or utilisation by the greatest number of vehicles, for example –

- minimising total cost while maximising covered demand (Huang and Kockelman, 2020). "Boston-network results suggest that EVCSs should locate mostly along major highways, which may be a common finding for other metro settings." Location chosen for "special existing infrastructure like parking lots and gas stations" or at network intersections.

- linking with traffic assignment models to capture traffic congestion and queuing impacts at the charging sites.

Charger planning is rarely considered from a multi-disciplinary perspective in the literature. Maia, Teicher and Meyboom (2015) looked at EV charging sites from a broader "synthetic human-centered design perspective", including the design and branding, business model, and phasing of the stations. The authors note that EVs are "discontinuous innovations" which require significant modifications of behaviours and associated products and services. They give the example of the Transportation Infrastructure and Public Space Laboratory at the University of British Columbia (TIPSlab) charging station project which ran between 2011–2014. The project took a holistic approach to deploy 450+ stations that considered how the public chooses its transportation mode. Deploying EV infrastructure to promote EV demand requires prediction of that demand, made possible by extrapolating existing data. This served to modify the objective priorities of the EV infrastructure over time, aligning the EV adoption phases (visibility and convenience are first priorities while innovators are adopting, while cultural branding, reliability and affordability shift to the dominant priorities as early adopters and early majority adopt, followed by cost, competitiveness, gas vehicle displacement and energy use).

Many public charging infrastructure 'guides' also comment on non-engineering aspects especially safety and aligning with amenities (shopping, cafés, toilets etc.). The reason cited is often connected to boosting the value proposition of EV infrastructure (increased revenue if the infrastructure owner is the shop owner, or to get deals with local business owners to provide funding if the infrastructure owner is not the business). Stress is placed on the importance of creating a 'brand' for EV charging stations like petrol stations have done. An example of such guides is the Everty guide.

There is a lack of understanding about relationships between different kinds of infrastructure planning, how different networks connect, and how this in turn shapes the user experience. There is significant variation in the kinds of companies installing chargers, ranging from community centres installing a single charger to large companies setting up national networks. Crown Hotels, for example, installed Tesla chargers across its entire network in 2018 (Fenech, 2018). We do not know how businesses make decisions about charger installation, and what impacts and benefits chargers generate for businesses and for charging infrastructure networks and transport systems more generally.

Integration with urban planning and governance

Streets are a key site in cities, an important focus not just for transport but for social and economic exchange. Changes in the allocation and regulation of streets are often highly contested and dependent not only on technological shifts but also social norms and understandings (Thorpe, 2020; 2021). Docherty and Dowling (2020) examines the impacts of new mobility services– including EVs, home delivery, ride hailing services, charge points, car and bike sharing programs on curb sides. A range of new actors are now vying for curb-space access. "Moving to a more flexible use of curb space is not a trivial thing. It will imply design changes, engineering and construction costs (including knock-on congestion costs), revisiting the regulatory treatment of different transport modes and their access to public space (including anti-competition oversight), modifying or designing new revenue-collecting mechanisms, accounting for changes in peoples' travel behaviours and integrating a wide range of sometimes conflicting stakeholder concerns.

It is likely that the impacts of curb space reallocation on the location and availability of parking will likely be this must be carefully considered."

ITF (2018) look at the different curbside stakeholders, their uses, motivations, and means of influencing their 'ownership.' The UK Strategy to 2040 states that "We want all new street lighting columns to include charging points, where appropriately located, in residential areas with current on-street parking." (DfT, 2018). The strategy mentions two case studies, one from Sydney Australia and one from the UK, where curb-side EV charging points were installed in areas previously deemed unsuitable for parking. Where charge points take up footway space, the result is the reallocation of space from pedestrian amenity to the fuelling of vehicles. "E-taxis in particular will require rapid charging and so are being given a dedicated network of charge points to stimulate uptake. E-car club vehicles will also require more rapid, and potentially exclusive, charging infrastructure."

Sustainable mobility and impacts of trend convergence

Some commentators in the electricity industry and a number of transport academics see trends towards electrification, mobility-as-a-service and automation. These trends are anticipated to converge at some point (Sperling, 2018). Most of the literature examining charging behaviour assumes the traditional reliance on private, non-autonomous, individual automobility. Yet already "a number of studies indicate a decreasing attachment to the automotive mode of transport particularly in younger age cohorts" (Webb, 2019). For example, the rise of car sharing is seen "not only as an outcome of cost, but also of some seminal shifts in consumer preferences" (Webb, 2019). How trend convergence might impact EV integration with the grid has not been considered but could be expected to radically change this relationship.

Two significant trends are the rise in car and ride sharing and the rapid growth in e-bikes and e-scooters (including both personal ownership and sharing services). E-bikes in particular have seen dramatic spikes in popularity as a result of the Covid pandemic (Alter, 2021; Sutton, 2021).

Australia is not immune from automobility preference changes. Despite a longstanding culture of automobile dependency (Kenworthy and Laube, 1999), the ridesharing and carsharing industries in Australia are growing fast. Uber has committed to electrify its fleet by 2040 (Dara Khosrowshahi, 2020) and recently announced an incentive for its drivers in Australia to swap to electric vehicles, offering them a 50% cut in service fees from July 2021 to June 2022 if they do.

In Australia and internationally, subsidies and incentives for electric mobility have focused primarily (in many cases exclusively) on cars. Despite this, e-bikes sales are still outstripping sales of electric cars by a considerable margin. According to the World Economic Forum, e-bikes are now selling at more than twice the rate of cars in the US and ratios are similar across Europe (Fleming, 2021).
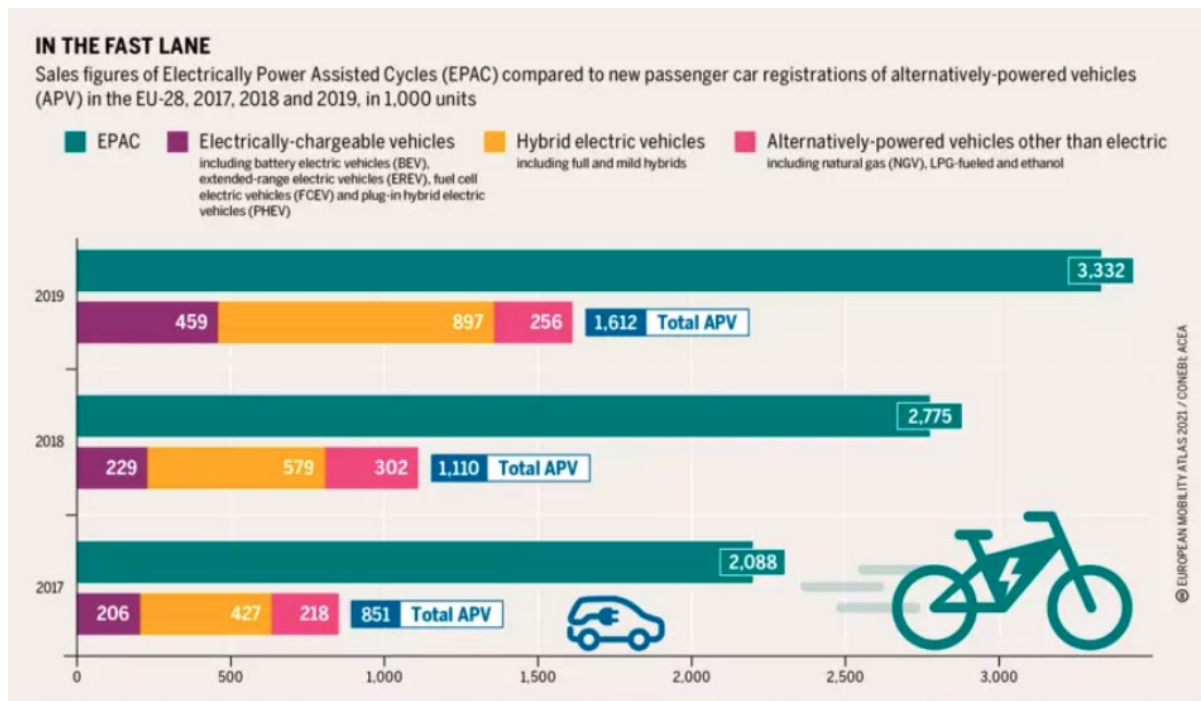
IN THE FAST LANE

Sales figures of Electrically Power Assisted Cycles (EPAC) compared to new passenger car registrations of alternatively-powered vehicles (APV) in the EU-28, 2017, 2018 and 2019, in 1,000 units

- ■ EPAC
- ■ Electrically-chargeable vehicles
  including battery electric vehicles (BEV), extended-range electric vehicles (EREV), fuel cell electric vehicles (FCEV) and plug-in hybrid electric vehicles (PHEV)
- ■ Hybrid electric vehicles
  including full and mild hybrids
- ■ Alternatively-powered vehicles other than electric
  including natural gas (NGV), LPG-fueled and ethanol

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Figure 23. Electrically power-assisted cycle vs alternatively-powered vehicles

Supporting greater adoption of electric carsharing and ridesharing and, particularly, of electric bikes and scooters could have significant benefits for equity. While the price of electric cars puts them out of reach for many people, sharing and micro-mobility are far more accessible. Relatively small government investments could increase this considerably. In France, for example, the government recently introduced a €2,500 subsidy for people who trade in cars to purchase an electric bike (Reuters, 2021). Given that many of the burdens of car-centric development – deaths and accidents, locational disadvantage and displacement due to infrastructure, air and water pollution among others – are borne disproportionately by communities that are already marginalised, increasing electrified micro-mobility and shared automobility among these communities could significantly improve these factors (Culver, 2018; Henderson, 2020). Equity improvements will not automatically follow, however. Research in Italy found that while car sharing increases accessibility levels for everybody in absolute terms, in relative terms the spatial availability of this service is greater for wealthier households than for lower income households (Pede and Staricco, 2021).

Even more than subsidies, infrastructure will be crucial to the uptake of these technologies (Alter, 2021). Bicycle parking, secure charging facilities, safe, separate lanes for bicycles, and priority lanes for shared cars will be important to maximise the benefits of electrification.

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Research opportunities

There is a significant gap in understanding how and why charging infrastructure (including public chargers) is planned as well as what are the regulatory and other barriers to the installation of private chargers (e.g., in apartment buildings and workplaces) and what the consequences of those planning decisions will be. We also do not yet understand the impact of EVs on mobilities, particularly sustainable forms of transport like walking, cycling, and public transport, as well as car and ride sharing. Travel behaviour generally remains poorly understood, as do shifts in mobility prompted by Covid-19. Research is essential to understand how the development of EV infrastructure and policy can encourage sustainable mobility options.

D.Potentials and Barriers

This section outlines the potentials and challenges of successful EV integration to the grid.

1. Technology and market potentials

The market potential for a sophisticated roll out of grid integrated EVs is large. If we assume that one million vehicles are sold each year and that by 2030 under some scenarios this could be dominated by EVs, then the opportunities for investment and benefits from achieving optimal outcomes will be in the billions of dollars.

Sales of EV chargers can be expected to ramp up to be in the range of hundreds of thousands per year, and the cost difference between standard chargers and smart chargers is estimated to be around $1000 in coming years - this alone is a $100M a year difference to an emerging market.

In terms of the operational benefits using integrated charging systems could avoid increased peak loads and in fact reduce peak loads by several gigawatts. The avoided cost for a gigawatt of transmission, distribution network and substation capacity is in the billions of dollars.

The impact on economic costs, emissions, and power network operation and controls depends on EV penetration and charging/discharging strategies. Uncoordinated charging operations for example tend to increase the load at peak hours and can cause problems on power grid operation and control. Incentivised EV charging pricing policy has been highlighted as one of the highest priority initiatives needed to enable a smooth transition to grid-integrated EVs. Implementation of real-time and ToU pricing options would encourage EVs to minimise constraints and maximise opportunities through their integration into energy systems.

2. Barrier analysis

Uptake of electric vehicles (EVs) is likely to increase in the future, although the rate and extent of uptake is highly uncertain. It is clear that uptake of EVs is desirable from an environmental standpoint even when using fossil fuel powered electricity, and carbon emissions will be greatly reduced when the majority of electricity is provided through low carbon technologies. If as a community we wish to see the uptake of EVs maximised, it is important that the barriers to uptake of EVs are managed and/or removed. Barriers relating to vehicle cost and 'range anxiety' are important but not the focus of the RACE CRC and have been addressed elsewhere. The focus of this analysis is the barriers relating to the impact of charging (and discharging under V2G scenarios) of EVs on the distribution networks. Of course it is difficult to completely dissociate the barriers that relate to ownership of EVs with the impact on the grid, so some overlap in the analysis will be present.

As the penetration of EVs increases, there will be a host of challenges relating to grid stability, orchestration of charging, charging hardware standards, tariff structure etc. If the barriers can

be overcome, then the potential for EVs to be a net benefit to the grid through maximising utilisation of existing assets and even as a provider of peaking power through vehicle to grid (V2G) potential. To overcome the barriers, utilities, EV manufacturers and EV charging infrastructure sector can potentially enhance EV adoption by leading in development of intelligent EV charging infrastructure and managed charging strategies to accommodate customers' needs and to help EVs become interactive grid assets rather than unmanageable grid loads.

Although there is consensus on the potential of grid-integrated EV charging to assist in the transition to high penetrations of EVs, the various stakeholders have not agreed on or converged around a common 'managed charging' or 'bidirectional charging' set of protocols and appropriate business models are under-developed and fragmented.

The successful integration of EVs into our energy systems will eventually require the establishment of user-friendly and reliable hardware, software, and communication systems, as well as business models that generate benefits equitably across the stakeholder landscape at lowest possible cost with highest possible return. The project team conducted analyses of key barriers to successful EV-grid integration for the purposes of developing a prioritised research plan for the RACE CRC stream on EVs. The analysis identified 71 initial barriers classified under categories proposed by the RACE CRC (Table 1).

Short summaries of these barriers are outlined below.

Technical barriers

Direct grid barriers. Barriers in this sub-category include lack of optimal scheduling and controlled charging and management strategies; impact of uncoordinated and uncontrolled charging on power system security and stability; power quality, under-utilisation of grid capacity at non-peak times, increase in network power losses and operating costs; convenience of EV charging as well as installation/connection costs, and regulatory hurdles for both electrical connection and planning approvals for installation of grid-interactive public infrastructure and additional generation capacity.

Vehicle related barriers. Barriers in this sub-category include battery shelf life, battery cycle life and degradation trade-off as managed and bidirectional charging can impact negatively on battery life in certain circumstances. Further barriers are outdated trials and pilots of new vehicle and charging technologies, mobility shifts (change of landscape of managed charging as transport shift to ride-sharing & autonomous vehicles), integration of heavy transport (e.g., buses, trucks), and limitations on commercial vehicles. The absence of vehicle industries in Australia (i.e., no OEMs building cars) is a barrier to implementation as there is no cooperation between utilities and OEMs.

Other technical barriers. These include a lack of planning tools for optimal EV Service Equipment (EVSE) rollout, volatility and the intermittent nature of DERs (i.e., solar-PV), lack of modelling on

solar-storage and back-up in peri-urban areas and outer suburbs, and lack of preparation of public transport networks for Battery Electric Buses (BEB).

With respect to cost, barriers identified include high purchase price of EV, costs for software/hardware, operations, platforms, coordination, as well as costs for demonstration projects and trials of EV-Grid integration, costs of smart networked EVSE, and set-up costs for microgrids.

Institutional barriers

Regulatory. A number of barriers relate to regulatory and standardisation including the coordination of standardisation requirements/rules in different layers of the electrical grid network, lack of interoperability and hardware, software and communication standards, installation/connection regulatory hurdles, and regulatory and other constraints around bidirectional grid connections. Other barriers are the absence of no long-term planning, and lack of policies and incentives regarding energy market mechanisms and tariff structures for promoting G2V and V2G. Concerns over readiness planning tools and schemes for infrastructure roll out and lack of understanding of potential equity issues adds to the regulatory uncertainty.

Pricing. Barriers to efficient pricing include lack of offerings of ToU and dynamic pricing plans across most markets in Australia and the limited number of working business models for grid-friendly charging. High-capacity tariff structures are also currently a barrier to profitable public charging business, especially fast charging businesses.

Payback gap. A barrier here is the cost of integration technology investments by vehicle manufacturers, EV owners, networks and retailers compared to potential revenue/benefit to investors in this technology. Commercial viability of EV-Grid integration technologies is critical and has not yet been demonstrated.

Incentives. The fact that incentives are fragmented across many different EV and grid stakeholders creates barriers for EV integration. There are also too many permutations and combinations of technologies, standards, platforms, business models, customer interfaces etc. EV Owners//Networks as consumers may be reluctant to allow their EV to be managed for efficient and beneficial grid integration unless there are incentives.

Lack of information. Successful EV orchestration requires sound knowledge of the current state of EV as well as future travel and grid requirements at all times of connection to the grid. Utilities, aggregators and charge-point operators need real-time mobility data to understand customers' mobility preferences and requirements. Other lacking information includes business model examples or guidelines for setting up managed charging schemes, and uncertainty of speed and extent of uptake creates uncertainty around extent and type of grid integration investment and actions required, thus adding to this category of barriers.

Cultural barriers. Barriers in this category include poor understanding of what early adopters' decisions around purchasing, design preferences, charging and driving tell us about the likely

wider uptake. There is a poor understanding of recent and future charging behaviours and the extent to which the alignment between EVs and broadly post-materialist and environmental values will shape EV uptake. Further challenges include poor planning of charging infrastructure based on inadequate understanding of the social needs for transportation, and a lack of clarity on behavioural aspects of EV use: Given that DERs are currently largely customer driven, it is important to understand related behaviours until the time that regulatory conditions can be set to create optimal conditions for the grid and its customers.

Lack of coordination. Coordinated planning and interoperability of infrastructure including public transport planning is currently lacking due to an inadequate understanding of social needs for transport. Added to this are the expensive trials and demonstrations on EV-Grid integration, which currently appear to lack solid coordination of effort. Furthermore, extracting benefits from multiple value streams requires aggregation and coordination across all the potential revenue streams in order to realise full benefits.

2.1 Priority barriers

Priority barriers were identified through the IRG consultation process and prioritised based on the impact they have on the sector from an industry stakeholder perspective (those in the IRG) and the influence RACE for 2030 could have on resolving them. The results are shown in Table 6.

Table 6. Priority barriers of EV to successful EV-grid integration

	Barrier Category	Priority barriers
Technical	Current Technology	1a. Impact of uncoordinated and uncontrolled charging on grid security, stability, and reliability 1b. Safety of home charging infrastructure 1c. Grid integration and orchestration technology 1d Large/Heavy EVs and charging infrastructure availability
	Current costs	2. Software/hardware and installation/connection (land; permission) costs
Institutional	Regulatory failure	3a. Lack of standards on EV grid integration 3b. Concerns around interoperability and compatibility 3c. Other regulatory hurdles
	Inefficient pricing	4a. Understanding tariff structures, network demand, and time reflective price for customers; bills and customer pricing 4b. Market/business model
	Payback gap	5. Proving long term total cost of EVs and residual values
	Split incentives	6a. Value stacking for bidirectional charging 6b. Incentives for customer behaviour
	Lack of information	7a. Uncertainty on uptake forecasts 7b. Lack of information on customer travel behaviour 7c. Lack of data access and availability
	Cultural barriers	8a. Customer travel and charging behaviour patterns 8b. Customer equity 8c. Social acceptance of bidirectional charging 8d. Trust
	Lack of coordination	9a. Stakeholder uncertainty 9b. Energy, urban planning, and transport nexus 9c. Other external factors – hydrogen; storage technology

There was broad consensus on technical challenges, particularly those surrounding the impact of uncontrolled and uncoordinated charging on grid security, stability, and reliability. The uncertainty around the means for scheduling (i.e., technology – hardware and software), coordination, and (network) control of charging can exacerbate the minimum demand concerns of networks and contribute to evening peaks. Stakeholders also discussed the impact on power quality and power system integrity in the short, medium and long term particularly for Level 1 chargers. It is understood that Level 3 fast chargers do not cause power quality issues.

The other technical challenge predicted to emerge in the medium term is the lack of maturity of grid and EV orchestration/integration technologies and aggregation methods. This echoes the concern around managing bidirectional charging and control mentioned above. As with all technology, it is important to remember the user/customers and ensure the technical interface is seamless.

Stakeholders also discussed the role of large EV and subsequent charging infrastructure availability. Opportunities in transit vehicles, mining microgrids, and the like apparent in the

short to medium term were discussed. Other technical barriers evident in the short term included safety, particularly for home charging infrastructure, and the cost of technology and associated connection and installation costs.

The most discussed *institutional* barrier was the lack of real world data and information. This includes uncertainty around the speed and extent of uptake, impeded planning on required grid investment, as well as charging infrastructure and other resources required. The little information available from current technology adopters and enthusiasts is also not a good reflection of how the rest of the population will approach uptake. The concern expressed were not merely about data but also about the models/methodology used to deliver these forecasts.

The lack of access and availability of charging and load data is a key immediate concern. It is important to understand typical load profiles for network planning. Visibility, and then control at this level are required operationalise bidirectional charging business models. A related concern is access to these data and adequate customer protection and compensation framework. Also important for the medium term was the lack of tools and forecasts for customer travel and charging requirements. This links closely to the barriers discussed under the cultural category.

Market barriers discussed were around inefficient pricing, split incentives, and the payback gap.

- In the short term, stakeholders prioritised understanding user behavioural changes to pricing incentives, and developing appropriate tariff structures that address network demand charges through dynamic pricing for customers. High-capacity tariffs are a barrier for profitable (fast) public charging. In an industry where business models are not well established, uncertainty around tariff structure for EVs is a barrier to investment and innovation.
- There is a lack of understanding on value stacking for bidirectional charging. Electric vehicles provide the opportunity for new parties such as local governments and private citizens to use vehicles to create revenue through their interaction with the electricity grid (which will be of particularly interest to people that cannot have rooftop solar). Currently this opportunity is not well realised nor are the implications for energy utilities and other incumbent energy firms.

Cultural barriers are seen to come up mostly in the medium to long-term perspective, but they deal with pivotal issues of access, equity, and social licence.

- There is lack of information about, and understanding of, customer EV behaviour in terms of travel, uptake and ownership in general and charging in particular. There is little to suggest how incentives can be used to encourage charging behaviour that can offer network support during constraints or as a flexible demand service.
- Customer equity is an important consideration raised by stakeholders. While still nascent, it is vital to understand the potential equity issues that can arise as networks reach hosting capacity limits and access to network resources is limited.
- It is important to understand risk from a network and a customer perspective while developing bidirectional charging models. Like many other forms of DER involved in network service offerings, smart charging solutions need social acceptance from all parties involved.

Regulatory barriers addressed the overall policy uncertainty and lack of standardisation and coordination for grid integration of EVs in Australia.

- The lack of unified, future-proof standards for grid connection of EVs to enable them to be used as flexible demand and storage through managed and bidirectional charging, was highlighted by many stakeholders as a challenge that needs to be dealt with in the short to medium term. This is also linked to the unclear landscape for the standardisation of device performance, interoperability, and capability.
- Other regulatory challenges brought up were the impact of policy uncertainty on the responsibilities of different interested parties and the scope of EV options offered by manufactures. This also links to challenges associated with stakeholder uncertainty and the lack of coordination in the EV space.

E. Priority research projects

The opportunity analysis was presented to the IRG and the research partners to get feedback on industry priorities and to align research priorities with industry needs and customer requirements.

Overall, IRG agreed with the high-level list of opportunities captured and indicated priorities around four themes: data and technology, market and pricing, user practices and customer behaviour, and regulation and coordination. The following table is the summary of identified industry-based research projects.

Table 7. Summary of the project opportunities

Opportunity Areas	Project Items
a) *Charging implications*: EV- charging trends and impacts on grid stability, security, and reliability (1a, 1c)	· EV trials with whole-of-network approaches · Developing coordinated smart charging approaches · Understanding changing transport patterns and related energy dynamics · Developing strategies for local governments and EV charging
b) *EV uptake*: Forecasting the impact of EV uptake and other external factors on the electricity network (7a, 9c)	· Data studies on trend analysis and tipping points · Improving network visibility to see EVs and EV chargers · Developing common load profiles based on uptake data
c) *EV data*: Data hub for EV travel behaviour and the grid, building customer trust for vehicle grid integration (7c, 8d)	· Creating an independent data curator/concierge · Strategies to inform customers perception of EVs and energy storage not just transport · Education, awareness, and customer engagement strategies
d) *Charging patterns*: Behavioural insights on EV charging patterns (7b, 8a)	· Behaviour studies on customer attitudes and drivers · Observer user behaviour studies and surveys · Identifying hooks and avenues for messaging and engagement
e) *EV tariffs*: Tariff design and its impact on EV charging behaviour (4a, 6b)	· Understanding price sensitive demand of EVs · Tariff design and impact on customer behaviour to shift loads

f) *EV standards and codes*: Technical standards and requirements for vehicle grid integration, interoperability requirements and protocols for EV charging (1b, 3a, 3b)	· Technical standards for of bidirectional chargers · Standards and protocols for communication · Interoperability protocols to streamline information exchange
g) *New Business Models*: New business models for various use cases, value-stacking of bidirectional charging, equity, and social acceptance (4b, 6a, 8b, 8c)	· Investigating new business models for EV charging and storage in Australia · Demonstrating specific value streams and value stacking opportunities for bidirectional charging of EVs · Understanding key equity and social acceptance areas and considering the role of government
h) *Urban EV nexus*: Transport integrated grids and precincts (including heavy EVs), and regulatory conditions (1d, 3c, 9b)	· Demonstrating how energy grids can interact with transport systems and urban development for mutual benefit · Understanding specific considerations for various types of heavy vehicles and public transport options · Exploring regulatory and other constraints associate with the integration of energy, mobility and development

F.Impact Framework

1.1 Impact Categories and Key Performance Indicators

The activities and outputs listed in Table 8 are derived from the research opportunities identified in the opportunity assessment. The list is broad but should not be considered exhaustive. An individual project may consist of multiple activities and outputs described here or propose new ones. This section focuses on identifying key performance indicators (KPIs) and metrics for three categories of outcomes: knowledge and technology diffusion; industry development; and societal impact. Each outcome type is subdivided into a number of outcome sub-categories, and there is at least one KIP and often several associated with each sub-category. Similarly, each KPI has at least one metric, though often several.

1.2 Knowledge and Technology Diffusion

Table 8.Categories and indicators for knowledge and technology diffusion outcomes

Category	Indicators	Metrics
Knowledge, Awareness & Skills	Better understanding through knowledge diffusion.	Self-reported change by industry stakeholders.
	Specialised skill development.	# of people trained. # of skill sets identified.
Attitudes	Social acceptance of bidirectional charging / vehicle grid integration. Customer participation in wholesale markets and network support	# of networks buying non-network support services. Change in connection agreements. MW of non-network support traded
Technology & process innovation diffusion	Increased uptake of VGI products & services.	Product /services sales #. # of Retailers / aggregators offering services.
	Increased uptake of tools & methodologies for better network planning in existing businesses.	# of businesses adopting tools.
	Mainstreamed business models: · Equitable pricing models tailored to time and location	# of businesses adopting models.

1.3 Industry Development

Table 9.Categories and indicators for Industry development outcomes

Category	Indicators	Metrics
Reducing Barriers to VGI	Increased visibility of LV network.	· Use cases implemented · % visibility on network
	Optimal EV penetration / Increased Hosting Capacity.	· Grid decentralization ratio · % EV with managed or bidirectional charging on LV feeders
Network Operations	Improved network utilisation.	· % Utilisation · Annual load variation curve
	Network operates within limits of all applicable quality standards.	· Annual average breach hours / day · Occurrences of overvoltage and undervoltage events. · Power quality metrics (e.g. voltage sags, swells and fluctuation, phase unbalance, transients and harmonics)
Policy & Regulation to support informed decision making & investment planning	Influenced decision making / decision-makers.	· Evidence of policy change – reports, guidelines, etc. · Citations in key industry decision-making forums
	Informed changes in industry policy, market rules, legislation, regulations or guidelines.	
Customer Satisfaction & Equity	Equitable access to network resources and benefits.	· Network connection agreements · Customer complaint rates

1.4 Societal Impacts

Table 10. Impact indicators and metrics

Category	Indicators	Metric
Economic	Lower energy bills	$ (bill reduction)
	Lower network costs	Network LCOE
Economic / Environmental	Increased energy system reliability	Change in Disruption Index
Environmental	Reduced emissions	CO_2 equivalent
Economic / Social	New jobs created	FTE

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Appendices

Appendix 1. Barriers Analysis on Electric Vehicle Grid Integration, Policy Regulatory Frameworks and Standards

This report provides a comprehensive list of barriers to the large-scale integration of electric vehicles to power grids. Barriers have been analysed under the following three categories: 1) Integration of Electric Vehicles in Power Grids, 2) Policy Regulatory Frameworks, and 3) Standards and Grid-Codes.

2. Barriers to Integration of Electric Vehicles in Power Grids

The barriers to large-scale integration of electric vehicles to power grids are analysed under four major areas; 1) Network Barriers, 2) System Operation and Control Barriers, 3) Barriers to Vehicle to Grid (V2G) Operation, and 4) Barriers to EV orchestration with Distributed Energy Resources (DERs).

2.1 Network Barriers

The major network barriers to EV grid integration are listed below.

- **A1**: Violation of network voltage limits stipulated in grid codes (Dubey and Santoso, 2015) (Vassileva and Campillo, 2017) (Habib *et al.*, 2018) (Deilami *et al.*, 2011) (Brenna, Foiadelli and Longo, 2014) (Laura Jones *et al.*, 2021)
- **A2:** Violation of capacity limits of network assets (e.g., transformers), protection malfunction and network congestion (Zhou, Littler and Wang, 2013) (Zeng *et al.*, 2017) (De Simone and Piegari, 2019) (Spitzer *et al.*, 2019) (Laura Jones, Kathryn Lucas-Healey, Björn Sturmberg, Hugo Temby and Monirul Islam, 2021)
- **A3:** Added network augmentation cost and reluctance of utilities to invest on network upgrades (Yilmaz and Krein, 2013b) (Knezović *et al.*, 2017) (Shariff *et al.*, 2019) (Habib *et al.*, 2018) (Dale Hall, Nic Lutsey, 2017) (Governor Edmund G. Brown Jr., 2013)
- **A4:** Increase in network power losses and operating costs (including distribution transformer losses) (Zheng *et al.*, 2019) (Dubey and Santoso, 2015) (Deb *et al.*, 2018) (Das *et al.*, 2020) (Habib *et al.*, 2018) (Yilmaz and Krein, 2012)
- **A5:** Violation of network power quality limits (harmonic distortion and peak demand) (Zheng *et al.*, 2019) (Yilmaz and Krein, 2013b) (Das *et al.*, 2020) (Habib *et al.*, 2018) (Yilmaz and Krein, 2012)

2.2 System Operation and Control Barriers

- **B1:** Lack of evidence on reliability and performance of the electric grid with EVs (Zeng *et al.*, 2017) (Deb *et al.*, 2018) (Habib *et al.*, 2018) (Laura Jones, Kathryn Lucas-Healey, Björn Sturmberg, Hugo Temby and Monirul Islam, 2021)
- **B2:** Difficulties of identifying strategic network locations for fast chargers or charging stations (lack of optimal location selection strategies) (Deb *et al.*, 2018) (Yilmaz and Krein, 2013a) (Hussain *et al.*, 2021) (Mather, 2020)

- **B3:** Impact of uncoordinated charging of EVs on power grid economic and technical performance (Deb *et al.*, 2018) (Yilmaz and Krein, 2013b) (Dubey and Santoso, 2015) (Clement-Nyns, Haesen and Driesen, 2011) (Solanke *et al.*, 2020) (Knezović *et al.*, 2017) (Alghsoon, Harb and Hamdan, 2017) (Clement-Nyns, Haesen and Driesen, 2010) (Deilami *et al.*, 2011) (Hussain *et al.*, 2021) (Laura Jones, Kathryn Lucas-Healey, Björn Sturmberg, Hugo Temby and Monirul Islam, 2021)
- **B4:** Impact of uncoordinated and uncontrolled charging of EVs on the power system security and stability performance (steady-state and transient) (Haidar, Muttaqi and Sutanto, 2014) (Deb *et al.*, 2018) (Zheng *et al.*, 2019) (Zhou, Littler and Wang, 2013) (Zhou, Littler and Meegahapola, 2016) (Spitzer *et al.*, 2019)
- **B5:** Placing of charging stations at remote locations (network busbars with low short-circuit ratio) results in a detrimental impact on voltage stability, reliability, power loss, and economic losses (Haidar, Muttaqi and Sutanto, 2014) (Deb *et al.*, 2018) (Zheng *et al.*, 2019) (Zhou, Littler and Wang, 2013) (Alghsoon, Harb and Hamdan, 2017) (Habib *et al.*, 2018) (Zhou, Littler and Meegahapola, 2016)
- **B6:** Additional generator startups and shutdowns (increased cycling) results in high operation and maintenance costs for generating stations and a lack of flexible generation (García-Villalobos *et al.*, 2014) (Zheng *et al.*, 2019) (Alghsoon, Harb and Hamdan, 2017) (Habib *et al.*, 2018) (Yilmaz and Krein, 2012)

2.3 Barriers to V2G operation

- **C1:** Lack of optimal scheduling and controlled charging strategies (García-Villalobos *et al.*, 2014) (Vassileva and Campillo, 2017) (Sovacool *et al.*, 2018) (Zheng *et al.*, 2019) (Patil and Nago Kalkhambkar, 2021) (Lund and Kempton, 2008) (Laura Jones, Kathryn Lucas-Healey, Björn Sturmberg, Hugo Temby and Monirul Islam, 2021)
- **C2:** Premature degradation of batteries and concerns of vehicle owners (García-Villalobos *et al.*, 2014) (Gough *et al.*, 2017) (Saldaña *et al.*, 2019) (Shariff *et al.*, 2019) (Yilmaz and Krein, 2012) (Yilmaz and Krein, 2013b) (Kejun Qian *et al.*, 2010) (Sovacool, Axsen and Kempton, 2017) (Laura Jones, Kathryn Lucas-Healey, Björn Sturmberg, Hugo Temby and Monirul Islam, 2021)
- **C3:** Lack of effective EV management solutions to increase network hosting capacity, and the potential provision of services to the grid (García-Villalobos *et al.*, 2014) (Quiros-Tortos, Ochoa and Butler, 2018) (Sovacool *et al.*, 2018) (Zhou, Littler and Wang, 2013)
- **C4:** Lack of data for the design of an electricity market mechanism for V2G (considering the behaviour of many EVs, operating conditions, quantification in a realistic manner, the true effects of EV charging load on the networks as well as on the overall system demand) (Haidar, Muttaqi and Sutanto, 2014) (Yilmaz and Krein, 2013b)
- **C5:** Co-incidence: Synchronous operation of V2G chargers could cause congestion in the network and could result in increased electricity price volatility (Laura Jones, Kathryn Lucas-Healey, Björn Sturmberg, Hugo Temby and Monirul Islam, 2021)
- **C6:** Increase of transformer cyclic/non-cyclic heating (due to abrupt bidirectional power-flows) and degradation of their lifetime (Quiros-Tortos, Ochoa and Butler, 2018) (Habib *et*

al., 2018) (Laura Jones, Kathryn Lucas-Healey, Björn Sturmberg, Hugo Temby and Monirul Islam, 2021)

- **C7:** The lack of real-time data of EV status to the grid operator and a similar lack of on-board/off-board intelligent metering (Yilmaz and Krein, 2013b) (Mwasilu *et al.*, 2014) (Zheng *et al.*, 2019) (Hu *et al.*, 2016) (Yilmaz and Krein, 2012)
- **C8:** Social barriers for V2G operation and public acceptance (requirements to store energy for the emergency purpose/ unpredictable journeys and range anxiety) (Sovacool *et al.*, 2018) (Shariff *et al.*, 2019) (Broadbent, Drozdzewski and Metternicht, 2018) (Laura Jones, Kathryn Lucas-Healey, Björn Sturmberg, Hugo Temby and Monirul Islam, 2021)

2.4 Barriers to EV orchestration with DERs

- **D1:** Volatility and intermittent nature of DERs (i.e.,, solar-PV) and a lack of appropriate forecasting models for distributed DERs (Richardson, 2013) (Lund and Kempton, 2008)
- **D2:** The lack of intelligent control techniques/ platforms to regulate the energy flow between the low-voltage power grid, renewable energy sources and the EV batteries (Ashique *et al.*, 2017)
- **D3:** Potential impact on grid stability and power quality due to the intermittent nature of PV energy and uncertainty of EV load (added uncertainty) (Tavakoli *et al.*, 2020) (Harvey, 2018)

A meta-analysis on the robustness of the above-listed barriers has been conducted considering the source data underpinning these studies, viz.:

a) **Observations from real network data/ operations (ranking score- 3)**

b) **Observations from field trials and pilot projects (ranking score- 2)**

c) **Proven by academic research studies (based on highly cited research articles) (ranking score- 1)**

Table 11 Analysis of EV Grid Integration Barriers

Barriers to Integration of Electric Vehicles in Power Grids	Criteria			
	a. Observed from network data	b. Observed from trials	c. Supported by research studies	Total Ranking Score (0-6)
1.1 Network Barriers				
A1: Violation of network voltage limits stipulated in grid codes	√	√	√	6
A2: Violation of capacity limits of network assets (e.g., transformers), protection malfunction and network congestion	√	×	√	4
A3: Network Augmentation Cost and reluctance of utilities to invest on network augmentations	×	√	√	3
A4: Increase of network power losses and operating costs (including distribution transformer losses)	√	×	√	4
A5: Violation of network power quality limits (harmonic distortion, and peak demand)	√	√	√	6
1.2 System Operation and Control Barriers				
B1: Lack of evidence on reliability and performance of the electric grid with EVs	×	×	√	1
B2: Difficulties of identifying strategic network locations for fast chargers or charging stations (lack of optimal location selection strategies)	×	√	×	2
B3: Adverse impact of uncoordinated charging of EVs on power grid economics and technical performance (lack of optimal charging)	√	√	√	6
B4: Impact of uncoordinated and uncontrolled charging of EVs on the power system security and stability performance (steady-state and transient)	√	√	√	6
B5: Placing of charging stations at remote locations (network nodes with low short-circuit strength) results in a detrimental impact on voltage stability, reliability, power loss, and economic losses	×	×	√	1
B6: Additional generator start-ups and shutdowns (increased cycling) result in high operating and maintenance cost for generating stations and the lack of flexible generation sources	√	×	√	4

1.3 Barriers to V2G operation				
C1: Lack of optimal scheduling and controlled charging strategies	√	×	√	4
C2: Premature degradation of EV batteries and concerns of vehicle owners of the overall health of the EV	√	×	√	4
C3: Lack of effective EV management solutions to increase network hosting capacity, and the potential provision of services to the grid	√	×	√	4
C4: Lack of data for the design of an electricity market mechanism for V2G (considering the behaviour of many EVs, operating conditions, quantification in a realistic manner, the true effects of EV charging load on the networks as well as on the overall system demand)	√	×	×	3
C5: Co-incidence: Synchronous operation of V2G chargers could cause congestion in the network regions and could result in volatility electricity prices	×	×	√	1
C6: Increase of transformer cyclic/non-cyclic heating (due to abrupt bidirectional power-flows) and degrade their lifetime	×	√	√	3
C7: Lack of real-time data of EV status to the grid operator and lack of on-board/off-board intelligent metering	×	×	√	1
C8: Social barriers for V2G operation and public acceptance (requirements to store energy for the emergency purpose/ unpredictable journeys and range anxiety)	√	×	√	4
1.4 Barriers to EV orchestration with DERs				
D1: Volatility and intermittency of DERs (i.e., solar-PV) and lack of appropriate forecasting models for distributed small-scale DERs (e.g., domestic PVs)	×	×	√	1
D2: Lack of intelligent control techniques/ platforms to control the energy flow between the low-voltage power grid, renewable energy sources and the EV batteries	×	×	√	1
D3: Potential impact on grid stability and power quality due to the intermittent nature of PV energy and uncertainty of EV load (added uncertainty)	×	×	√	1

Based on the analysis presented in Table 11, barriers were ranked based on the total ranking score received by each barrier. The distribution of the ranking score for the barriers listed in Table 11 is listed in . Figure 24.
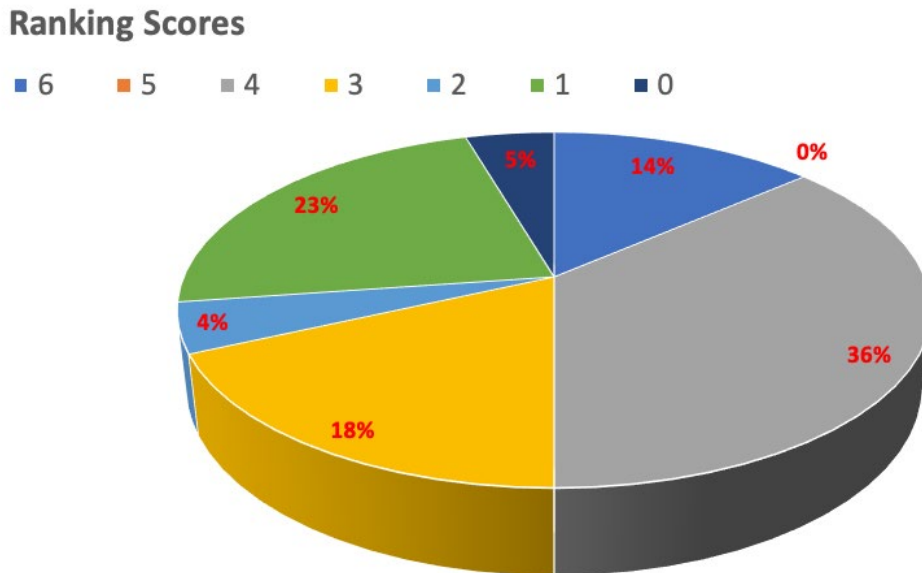

Figure 24 Distribution of Ranking Score for Barriers Listed in Table 11.

Based on the ranking score, the major EV grid integration barriers were identified, and they are listed below.

Major EV Grid Integration Barriers

- Violation of network voltage limits stipulated in grid codes

- Violation of network power quality limits (harmonic distortion and peak demand)

- Adverse impact of uncoordinated charging of EVs on power grid economic and technical performance

- Violation of capacity limits of network assets and congestion

- Impact of uncoordinated and uncontrolled charging of EVs on the power system security and stability performance (steady-state and transient)

- Additional generator startups and shutdowns (increased cycling) result in high operating and maintenance cost for generating stations and the lack of flexible generation sources

Secondary Barriers to Grid Integration of EVs

- Increase of network losses and operating costs (including distribution transformer losses) (distribution transformer losses)
- Lack of optimal scheduling and controlled charging strategies
- Premature degradation of batteries and concerns of vehicle owners
- Lack of effective EV management solutions to increase network hosting capacity, and the potential provision of services to the grid

- Social barriers for V2G operation and public acceptance (requirements to store energy for the emergency purpose/ unpredictable journeys and range anxiety)

3. Policy Regulatory Frameworks

3.1 EV adaptation policies, directives, and targets of countries and regions

- **E1:** Lack of long-term planning and goals by regulatory regimes, such as integrated system/energy plans for EV grid integration (Bradley, 2013) (Broadbent, Drozdzewski and Metternicht, 2018)
- **E2:** Absence of policies /educational information to raise the public awareness on overall interaction of EV with the electrical grid system (Kester *et al.*, 2018) (Bradley, 2013) (Broadbent, Drozdzewski and Metternicht, 2018)
- **E3:** Lack of country-specific studies and EV grid integration forecasts (Broadbent, Drozdzewski and Metternicht, 2018)
- **E4:** Lack of encouragement on designing new electricity market mechanisms and tariff structures for promoting G2V and V2G (Kester *et al.*, 2018) (Broadbent, Drozdzewski and Metternicht, 2018)
- **E5:** Lack of policies to encourage smart charging and EV aggregation (Verma *et al.*, 2015) (Al-Ogaili *et al.*, 2019) (Bradley, 2013)

3.2 Policies and regulation of public transport and service fleet electrification

- **F1**: Lack of economic incentives in terms of relaxations on toll roads, ferries, parking, access to bus lanes, exemptions in driver's license, fiscal compensations etc.(Sierzchula *et al.*, 2014) (Zhou *et al.*, 2015) (Broadbent, Drozdzewski and Metternicht, 2018) (Petter Haugneland1 *et al.*, 2017) (Erik Lorentzen1 *et al.*, 2017)
- **F2**: Usage of different assessment approaches for the measurement of CO_2 emissions from electric vehicles to meet the national standards (non-uniformity in assessment) (Jochem, Babrowski and Fichtner, 2015) (Loisel, Pasaoglu and Thiel, 2014) (Manjunath and Gross, 2017)
- **F3**: Lack of awareness in transforming vehicle fleets (Sierzchula *et al.*, 2014) (Governor Edmund G. Brown Jr., 2013)

3.3 The existing government incentives to promote EV adoption in private sectors

- **G1:** Absence of policies on annual tax exemptions for EV owners (Sierzchula *et al.*, 2014) (Broadbent, Drozdzewski and Metternicht, 2018) (Broadbent, Drozdzewski and Metternicht, 2018) (Petter Haugneland1 *et al.*, 2017) (Lorentzen *et al.*, 2017). (Lasse Fridstrøm, 2021)
- **G2:** Lack of purchase subsidies (Sierzchula *et al.*, 2014; Broadbent, Drozdzewski and Metternicht, 2018) (Petter Haugneland1 *et al.*, 2017) (Lorentzen *et al.*, 2017). (Lasse Fridstrøm, 2021)
- **G3:** Lack of design policy instruments to promote EVs with extremely low CO_2 emissions. A mismatch between emissions and economic incentives for charging (Zhang, Cheng and Yang, 2016) (Saldaña *et al.*, 2019)

Major Policy Related Barriers

The major policy framework barriers are ranked based on number of times these barriers are identified and agreed to in various reports and research articles. The following are the major barriers identified from the policy regulatory perspective:

- The lack of specific electricity market products and feed-in tariff structures for promoting G2V/V2G or lack of electricity market products to encourage V2G participation to provide system support services.
- Lack of long-term planning and targets by regulatory bodies, such as integrated system/energy planning frameworks for EV grid integration
- Lack of design policy instruments to promote EVs with extremely low CO_2 emissions. A mismatch between emissions and economic incentives for charging
- Absence of policies on annual tax exemptions for EV owners
- Lack of design policy instruments to promote EVs with extremely low CO_2 emissions.

4. Standards and Grid Codes

Standardisation of the EV grid connection is important for the operation to be carried out worldwide. Some aspects of EVs, such as charging plugs, voltage chargers, contact between the vehicle and the chargers, fast and slow charging systems, safety measures for the safe operation of the vehicle and people's safety against electrical shocks, and on-board electrical energy storage for the vehicle, need to be standardized for the safe and reliable use of the EVs.

4.1 EV grid connection standards

- **H1:** Standardisation limitations on hardware and software for charging stations (barrier to lower equipment costs and the use of smart charging) (Saldaña *et al.*, 2019) (Dale Hall, Nic Lutsey, 2017)
- **H2:** Lack of standards on electric vehicle charging infrastructure and their grid integration (LV/MV) requirements (e.g., charging stations, smart charging) (Saldaña *et al.*, 2019)
- **H3:** Increases in the complexity and time taken to get compliance for the grid connection codes as V2G will require assessment as a generator (Laura Jones, Kathryn Lucas-Healey, Björn Sturmberg, Hugo Temby and Monirul Islam, 2021)
- **H4:** Lack of Coordination of standardisation requirements/ rules in different layers of the electrical grid network including end-user electrical infrastructure and poor defining of standards (Saldaña *et al.*, 2019)

4.2 Adaptation of grid-codes for EV adoption (in different Jurisdictions / countries)

- **I2:** In order to make EV distribution grid services possible, the deployment of infrastructure with embedded intelligence should be supported and promoted via standards and regulations in the near-future (Knezović *et al.*, 2017) (Habib *et al.*, 2018)
- **I2**: The national electricity rules (NERs) requirements can be a barrier to grid services from distributed resources, including V2G in Australia (Laura Jones, Kathryn Lucas-Healey, Björn Sturmberg, Hugo Temby and Monirul Islam, 2021) (rule changes required for NERs)

Major Standard Related Barriers

- Lack of standards on electric vehicle charging infrastructure and their grid integration (LV/MV) requirements (e.g., charging stations, smart charging) (Saldaña *et al.*, 2019)

- Increases the complexity and time taken to get compliance for the grid connection codes as V2G will require assessment as a generator (Laura Jones, Kathryn Lucas-Healey, Björn Sturmberg, Hugo Temby and Monirul Islam, 2021)
- Lack of Coordination of standardisation requirements/ rules in different layers of the electrical grid network including end-user electrical infrastructure and poor defining of standards (Saldaña *et al.*, 2019)
- The national electricity rules (NERs) requirements can be a barrier to grid services from distributed resources, including V2G in Australia (rule changes required for NERs)

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Appendix 2. EV Trials

Trial ($AUD Funding)	Country	Date	Description / Findings	Social Science	Pricing/ ToU	Managed	V2G/ V2H	Data sharing?
CHARGE ($XM)	UK Scotland	2019- 2022	SP Energy Networks Pilot study comprising smart charging technology trials coupled with combined transport/electricity network planning to help create an overarching map of where EV charge points will be required and where they can be best accommodated by the electricity grid. Partners include PTV Group (transport) Smarter grid solutions (public EV charging technology) EA technology (online connection tools). https://www.spenergynetworks.co.uk/pages/charge.aspx			X		X
Electric Nation Smart Charging ($XM)	UK	2016- 2019	673 smart chargers were installed at participants' homes to charge 40 different types, makes or models of EVs. 130,000 charging events captured. Trial was designed with three configurations: 1) Fully managed charging with no user control; 2) user-interactive app to charge on user demand or automatically meet travel demand; 3) Simulated TOU tariff via reward system for using off-peak charging. The trial showed that: 1) There is an inherent flexibility in charging requirements for vehicles based on travel demand and battery characteristics in the trial; 2) Demand management was implemented successfully from both technical and user acceptance angles; 3) ToU incentives were shown to shift peak demand; 4) User-interactive smart charging (with an app), which makes it simple for the user can support sophisticated ToU management and assist to manage any negative consequences of mass uptake of ToU incentives; https://www.electricnation.org.uk/wp-content/uploads/2019/07/Electric-Nation-Trial-Summary-A4.pdf		X	X		
Jemena Dynamic EV charging ($3.4M)	AUS	2020-	176 Vehicles across ACT, VIC, TAS will be recruited to: 1)demonstrate use of managed charging in the home; 2) monitor the impact of these EVs on the local electricity networks; 3) gauge the willingness of consumers to have their EV charging managed; The broad aim is that project findings will help networks to better plan for EV uptake with minimal costs and maximum convenience for consumers. Partners: Jemena, AusNet Services, Evoenergy, Jet Charge, Tasmanian Networks (TasNetworks), United Energy https://IRENA.gov.au/projects/jemena-dynamic-electric-vehicle-charging-trial/		?	X		

Origin Energy EV Smart Charging Trial ($2.92M)	AUS	2020-	150 vehicles across ACT, NSW, QLD, SA, VIC. This trial aims to evaluate the benefits of and barriers to controlled smart charging, and improve understanding of EV driver behaviour, willingness to accept managed charging and what incentives are needed to encourage participation in charge management. Focus: to demonstrate managed charging on residential & commercial premises. Partners: United Energy Distribution Pty Limited, Ausgrid Operator Partnership, Nissan Motor Co. (Australia) Pty. Ltd, Hyundai Motor Company Australia Pty Limited, Custom Service Leasing Pty Ltd, Schneider Electric (Australia) Pty Limited, GreenFlux Assets B.V. https://IRENA.gov.au/projects/origin-energy-electric-vehicles-smart-charging-trial/	X		X		
Victorian Electric Vehicle Trial ($5M)	AUS	2009-2014	54 vehicles in Victoria, cycled through 178 configurations/households. Focus: Early demonstrate an EV ecosystem demonstrate managed charging on residential & commercial premises. The broad aims of the trial were to: 1) Raise awareness, understanding and acceptance of EVs in the Victorian community; 2) Demonstrate a real-world working "EV ecosystem" to better understand how people will use and recharge their EVs; 3) Provide information and insights to enhance the adoption of EVs and to help reduce the costs of EV uptake into the future. Partners: more than 70 partners across the EV ecosystem (vehicles, energy, charging, govt). Outputs from the trial include a report and a peer reviewed journal paper that analysed the trial data, presented it in a statistical model suitable for undertaking simulations, and projected that based on the trial data and further modelling, the power demand in 2032 for Victoria would increase by between 5-9% due to EV charging under expected scenarios. Mid-Term Report. https://apo.org.au/sites/default/files/resource-files/2013-06/apo-nid34464.pdf Statistical modelling of trial data - http://dx.doi.org/10.1016/j.trd.2014.08.017	X		X		X

My Electric Avenue (UK)	UK	18 mths	100 Nissan Leaf drivers arranged in geographical clusters in UK. This trials aim was to measure charging impacts on low voltage electricity networks from clusters of EVs with and without managed charging technology. Modelling study plus 100 Leaf drivers in clusters with and without managed charging Modelling work projected a doubling of the after-diversity maximum demand from around 1 to 2 kW and this was extrapolated across Britain with projections that 32% of low voltage network will require intervention when 40% – 70% of customers have EVs. The trial successfully tested a charging management system that used temporary curtailment of recharging on a rolling basis (typically, for 15 minutes each) across the local cluster of EVs to minimise this increased demand. Subsequent modelling predicted that the use of the charge management technology would provide an economic benefit through network upgrade deferrals of around £2.2 billion. http://myelectricavenue.info/sites/default/files/documents/Summary%20report.pdf					
AGL EV Orchestration Trial ($8.25M)	AUS	2020-2023	300 vehicles across QLD, NSW, VIC, SA . Focus: Demonstrating various EV orchestration and V2H technologies and strategies. AGL's EV orchestration trial aims to address the key uncertainties and risks surrounding EV charging orchestration – the commercial model, the technology solution, customer preferences and behaviour, and the broader market and regulatory arrangements. The project is focussed around several streams: 1) Assessment of EV orchestration benefits and trade-offs, using managed smart chargers installed in homes across a representative cross-section of DNSPs (200 Vehicles); 2) Evaluation of emerging technologies that have significant commercial potential: Vehicle API integration (50 participants), Vehicle-to-Grid (50 participants); 3) Assessing TOU tariffs by comparing customers using managed charging technology and those who are incentivised on price alone (100 participants); https://IRENA.gov.au/projects/agl-electric-vehicle-orchestration-trial/	X	X	X	X	?
Realising Electric Vehicles-to-grid Services ($6.3M)		2020-2022	51 vehicles in ACT. Focus: Demonstrating V2G for FCAS market. The Realising Electric Vehicles-to-grid Services (REVS) project aims to demonstrate a practical implementation of V2G, showing how EVs and chargers can contribute to energy stability by transferring power back and forth into the grid, as required. In this trial EVs will inject power back into the grid to provide support services during rare events (to avoid possibility of blackouts) and EV owners will be paid when their vehicles are used for this service. The trial is using 51 Nissan LEAF EVs across the ACT and is primarily demonstrating frequency support for the grid, with financial rewards based on the FCAS market. Partners: ANU. ActewAGL, Evoenergy,				X	

							X	X	
			Nissan, SG Fleet, JET Charge, ACT Government. https://IRENA.gov.au/projects/realising-electric-vehicle-to-grid-services/						
Electric Nation V2G ($4.1M)		2021-	90-110 Nissan Leaf vehicles with V2G equipment installed in domestic premises (Wallbox Quasar). The trial will explore and report on the impact of V2G charging on the low voltage (LV) electricity network, utilising end-user trial charging data and analysis. The trial will examine how dynamic bidirectional energy services based on vehicle battery storage, from a variety of energy suppliers, may impact the LV infrastructure. Results from the trials will be used to inform modelling to predict what extent V2G can assist with management of LV network demand, and to provide recommendations of policy and commercial frameworks on V2G services. https://electricnation.org.uk/				X	X	

Appendix 3. Annotated bibliography of Section C, Part 3.

The following document provides a summary of the key references researched to be used in preparing the literature review:

– *"Changing the course of Asia's transport sector through transformational change" Newman (2020)* cautions the total commitment to bringing in electric vehicles as the problems of automobile dependence mostly remain. It suggests that cities should prioritise electric buses, light rail and new trackless trams along main roads with stations which have local recharge hubs for all electro mobility especially targeting micro mobility. The integration of solar-based urban regeneration with this non-car dependent land development is a major tool for creating Net Zero Cities. The paper notes there is great need for transformational change in Asia's transport sector and if done strategically it can deliver a number of benefits for Asian cities. It describes a range of potential mechanisms now available to support such a transformation, including: transport policies, infrastructure development, technological intervention, institutional arrangements, and innovative financing mechanisms, among others. Key to the implementation of transformational approaches will be harnessing new and emerging technologies, including: electric mobility; the use of Artificial Intelligence and online distributed ledgers; integrated land-use and transport planning; and the activation of development opportunities along corridors using integrated shared transit. The way that these types of technologies are deployed will have a direct impact on the very functioning of cities in the coming decades.

– "*Identification and Analysis of Barriers against Electric Vehicle Use*' published in *Sustainability" Adhikari et al. (2020)* identified, analysed and ranked seventeen barriers against EV use. This analysis was formed through previous reports, studies, policy documents and interactions with experts. Barriers were classified according to five categories – technical, policy, economic, infrastructure, and social. The barriers were also identified in the context of EV uptake in Nepal, but it was noted that the framework can be applied to replicate the study in other countries. It was found that lack of charging infrastructure and lack of long-term planning and goals were among the highest barriers identified. They identified that "*appropriate legislation, geared toward the provision of a sufficient number of charging networks ... among other policies, should be included in long-term plans and goals for accelerated EV uptake.*"

– "*The evaluation of opportunities for the development of access for charging electric vehicles in the territory of apartment buildings" Palevičius et al. (2017)* is a proceedings for the International Conference on Environmental Engineering. It addresses the fact that the majority of EV owners live in private homes, likely due to the various difficulties residential apartment dwellers encounter when trying to charge their car in their building area at night. This article concluded that "It is likely that a denser network of electric car charging access points would inspire the use of electric cars. After the expert surveying and evaluation of weights of electrical vehicle access points in territories of apartment buildings it has been determined the most attractive territories (areas) for development of access points for electric vehicle charging to be in: shopping mall parking lots, lighting pole structures, and apartment building ground parking lots."

– "*Optimising the spatio-temporal deployment of battery electric bus system" Wei et al. (2018)* published in the Journal of Transport Geography identifies a method of minimising the cost associated with vehicle procurement and charging station allocation while maintaining existing

bus routes and schedules. This research is particularly important for implementation of Battery Electric Busses (BEB) in urban areas by helping transport agencies make critical decisions regarding the integration of BEB into their fleet. Traditional bus routes are based on transport demand instead of the location of fuelling stations. The location of charging stations along BEB routes presents a barrier for the uptake of EVs as suitable locations for required charging infrastructure does not always correlate to the areas of transport demand.

- *"Exploring the Decision to Adopt a High-End Battery Electric Vehicle: Role of Financial and Nonfinancial Motivations" Hardman and Tal (2016)* explores the decision to adopt high-end BEVs, such as the Tesla Model S. These vehicles are remarkably different from mainstream BEVs, and the adopters of these BEVs have been overlooked within the literature. An attempt is made to understand who is adopting high-end BEVs, why they are doing so, and how important financial incentives are for this group of adopters. Among the findings are: environmental, performance, and technological motivations are reasons for adoption; the new technology brings a new segment of buyers into the market; and financial purchase incentives are not important in the consumer's decision to adopt a high-end BEV.

- *"Electric vehicle adopters in Lisbon: motivation, utilization patterns and environmental impacts" ROlim et al. (2014)* this paper assesses electric vehicle users' motivations, daily patterns, and vehicle operation and management to understand the impact of EVs on travel, driving behaviour and the environment. It compares private and corporate users. Of particular interest are results on how, where and when drivers charge their vehicles. Difficulties raised include rapid changes in technology making it hard for governments to develop strategies and policy, the need for incentives (84% of respondents in European countries considered government incentives essential) and that consumer perceptions are currently shaped by EV disadvantages rather than advantages such as lower running costs.

- *"Measuring the cost-effectiveness of electric vehicle subsidies" Sheldon and Dua (2019)* examines the performance of US EV subsidies and suggests that cost-effectiveness can be improved by twofold by targeting incentives by income, vehicle disposal, geography, and/or vehicle miles travelled. The most cost-effective scenario is to limit subsidies to lower-income individuals – those with annual incomes under $70k (US) which will mostly target subsidies for those consumers who would otherwise not have purchased a PEV without the subsidy. Subsidies are more effective the closer they are to the point of sale.

- *"Simulating the value of electric-vehicle–grid integration using a behaviourally realistic model" Wolinetz et al. (2018)* examines how Vehicle–grid integration (VGI) between electric vehicles and the electrical grid may provide benefits that may include reducing the cost of using intermittent renewable electricity or providing a financial incentive for electric vehicle ownership. VGI is found not to increase the adoption of electric vehicles, but does have a small beneficial impact on electricity prices. By 2050, VGI reduces wholesale electricity prices by 0.6–0.7% (0.7 $ MWh–1, 2010 CAD) relative to an equivalent scenario without VGI. Excluding consumer behaviour from the analysis inflates the value of VGI.

- *"The urban recharging infrastructure design problem with stochastic demands and capacitated charging stations" Yildiz et al. (2019)* considers optimal placement of fast charging stations (typical recharge times 10 minutes) to inform investment decisions for all stakeholders (developers, city governments, fleet operators) using both mathematical optimisation and a

computer simulation of the Chicago metropolitan area. Optimisations are not sensitive to recharge trip numbers and require a relatively small number of charging stations. The authors also believe these insights will allow governments to design better incentive packages that would facilitate a faster transformation towards green transportation.

- *"Optimal Planning of Charging for Plug-In Electric Vehicles Focusing on Users' Benefits" Su et al. (2017)* shows it is possible to optimise grid operation while providing EV user benefits. The research looks at regular and irregular routes. The main contributions are: (a) a cost model of battery capacity degradation to estimate the battery costs of charging; (b) the cost of battery capacity fade of charging is significantly reduced by planning the charging SOC range; (c) simulation results prove that the grid load curve can be optimised by scheduling EVs with the constraints which occur in the process of maximizing EV users' benefits; and (d) the waiting time for getting into charging stations in busy areas is reduced by applying a method of queuing theory which combines different charging stations' queues into one according to queuing theory.

- *"Long-term strategic planning of inter-city fast charging infrastructure for battery electric vehicles" Xie (2018)* introduces a multistage chance-constrained stochastic model for strategic planning of battery electric vehicle (BEV) inter-city fast charging infrastructure. A model is developed to determine where and when charging stations are opened, and how many chargers are required for each station to meet the growing BEV intercity demand. The model is applied to a case study in California. This study showed 6 that investment in inter-city charging infrastructure is vital to alleviate the range anxiety. The model allows the level of service as an input.

- *"Placement of EV Charging Stations—Balancing Benefits Among Multiple Entities" Luo et al. (2017)* studies the problem of multistage placement of electric vehicle (EV) charging stations with incremental EV penetration rates accounting for the charging preference of the individual consumer (EV owner) to predict the aggregated charging demand at the charging stations. The EV charging industry is modelled as an oligopoly where the entire market is dominated by a few charging service providers (oligopolists). At the beginning of each planning stage, an optimal placement policy for each service provider is obtained, and through a series of experiments using the geographic and demographic data from the city of the San Pedro District of Los Angeles, CA, USA, shows that the charging station placement is highly consistent with the heatmap of the traffic flow. In addition, we observe a spatial economic phenomenon that service providers prefer clustering instead of separation in the EV charging market.

- *"Equitable distribution of recharging stations for electric vehicles" Chung et al. (2018)* investigates equitable access to charging stations among geographical regions. Equity constraints considered for recharging location models are based on travel demand and traffic flow, and the proposed models and computational method were tested on data from an expressway network in Korea. The results show that without equity constraints, models located charging stations only in densely populated regions. With the proposed model, equitable distribution is achieved with a small drop in available charging in denser regions.

- *"Deploying public charging stations for electric vehicles on urban road networks" He et al. (2015)* explores how to optimally locate public charging stations (within a set budget) for electric vehicles on a road network, considering drivers' spontaneous adjustments and interactions of

travel and recharging decisions. The proposed approach captures the interdependency of different trips conducted by the same driver by examining the complete ToUr of the driver. Given the limited driving range and recharging needs of battery electric vehicles, drivers of electric vehicles are assumed to simultaneously determine ToUr paths and recharging plans to minimize their travel and recharging time while guaranteeing not running out of charge before completing their ToUrs. The paper does not conclude with any specific insights however it would be a planning tool for organisations. deploying charging infrastructure.

– *"Multi-stage Planning for Locating Charging Stations for Electric Vehicles in Urban Networks"* Zamir and Haghani *(2017)* develops a two-stage stochastic optimization model for locating charging stations for electric vehicles in parking facilities located in urban areas which accounts for demand uncertainty in the future with the objective of minimising the users' deviation from their original destinations to park their vehicles at facilities that have chargers. The maximum number of chargers and budget are constraints.

– *"Research on Location Selection and Capacity Planning of Urban Electric Vehicle Charging Station"* Ma et al. *(2019)* considers Electric vehicles (EVs) as a kind of mobile micro-grid. With the gradual increase in numbers of EV owners, the layout and planning of charging stations is becoming more important. Considering the travel habits of urban residents, the load distribution of electric vehicles is predicted by Monte Carlo sampling from the perspective of predicting users' travel routes. The Affinity Propagation (AP) algorithm is used to find the clustering centre from multiple alternative locations and determine the optimal construction location of the charging station. The method fully considers the driving demand of electric vehicles and the actual situation of planning cities. An example is given to plan the charging station in the city, and good results are obtained from load forecasting to clustering out the charging station construction.

– *"Electromobility framework study: infrastructure and urban planning for EV charging station empowered by PV-based microgrid"* Sechilariu *(2019)* focuses on an experimental charging station integrated with a PV-based microgrid and able to interact with the public power distribution network via smart grid messages, with the EVs users and the surrounding building via a dedicated human machine interface. The experiment devised a multidisciplinary framework of electromobility, providing starting points for the design of intelligent bidirectional V2G charging infrastructure and an urban deployment methodology based on a multi-criteria analysis from a social acceptance survey, within the best fitting urban areas, within societal expectations and accounting for sustainability. The study highlights a research position that demonstrates the need of a systemic approach to remain centred on users' needs and habits, to assess efficiency at various scales of V2G, associated services, and the power grid.

– *"Coupled Charging-and-Driving Incentives Design for Electric Vehicles in Urban Networks"* Sohet *(2020)* investigates traffic system load management changing with the use of electric vehicles, due to how vehicle charging and range will affect commuters' driving style. It supports that vehicle charging and driving behaviours are linked together to affect traffic grid efficiency, from the consideration of energy in charging and personal route management. The model maintained Wardrop's Equilibrium for electric vehicle traffic, highlighting that EV traffic grids will be loaded similarly to conventional grids. Introducing central grid road tolling and cheaper fuel for fossil-fuel vehicles will lower their numbers in city inner areas and encourage the use of EVs instead.

- *"How Norway convinced drivers to switch to electric cars" Savage (2020)* describes the ways Norway encouraged uptake of EVs. The government began encouraging EV back in 1990 when the 25% VAT was scrapped for EVs. Then in 2001 the vehicle purchase tax was removed as well. EVs enjoy a 50% or greater discount on tolls and parking fees and the government has a principle that there should be a fast charger at least every 31 miles. The sale of new ICE vehicles will be banned by 2025. Problems that have emerged are crowded charging stations (19.5 EVs per charger) and that poorer people are relegated to second hand ICE vehicles.

- *"Local promotion of electric mobility in cities: Guidelines and real application case in Italy" Comodi (2019)* explores how local utilities can play a crucial role because they manage/own the local grid and therefore are the most important players to build public charging station infrastructure. The study consisted in a payback analysis of an investment in charging stations and showed that their capacity is a fundamental parameter to reduce the payback period and thus the investment risk. Required capacity is strongly influenced by the spread of the EVs but, at the same time, the spread of EVs depends on the spread of charging station infrastructure. Two way to overcome the impasse are suggested: supporting the charging station investment by combining it with the purchase of electric vehicles by the local utility itself, or gradually installing charging stations infrastructure starting from locations where a high capacity is needed. The paper demonstrated that an urban charging station infrastructure can be already profitable without incentives, with a payback period of 4– 9 years in the most conservative scenario.

- *"Review of electric vehicle charging station location planning" Kizhakkan (2019)* evaluates the effect of centralised strategic planning and optimization in charging station location selection, showing it drastically reduces the initial cost required to serve the EV charging demand and reduce range anxiety. This review paper focuses on the most significant parameters considered in charging station location planning by various research, its relevance and pitfalls.

- *"Temporal city-scale matching of solar photovoltaic generation and electric vehicle charging"Fretzen et al. (2021)* investigates the benefits of coordinated charging for EV and PV integration. The authors show how a simple coordination mechanism can drastically improve outcomes compared to generic uncoordinated charging behaviour, such as charging whenever a car parks or charging at a day's end. This gain does not come at a significant cost of EV availability for drivers, whereas opportunistic (un-coordinated) charging leads to low amounts of solar energy being absorbed by EV batteries. Even in scenarios with significant solar energy surplus (e.g., PV generation producing 426% of EV charging requirements in a scenario of 50% EV and 50% PV penetration) the share of solar energy of the entire charge can be small. A coordination strategy where EV charging times can be controlled via algorithm leads to gains of 22 or more percentage points, with little effect on drivers' range.

- *"Renewables self-consumption potential in districts with high penetration of electric vehicles" Bartolini (2020)* analyses the effectiveness of using large numbers of EVs in an urban district Osimo, Italy to balance its electricity grid, containing a range of generation sources including 23% non-controllable renewables (NCR), mostly PV. Initial simulation used Orimo's current number of EVs is 2600 (10% of fleet) in the deterministic hourly energy systems simulation model EnergyPLAN. Other models were simulated for different proportions of NCR and EV. The simulation showed that at current numbers, there was no need to export electricity from the micro-grid with all NCR energy absorbed by EVs. When NCR is doubled and EV penetration

increases to 30%, there is also no need to export electricity and Orimo's CO2 emissions are reduced by 17.5%. These results are reliant on smart charging infrastructure, which without (especially V2G) the total self-consumption of NCR would not occur at required grid load rates.

- "*Vehicle-To-Grid Technology in a Micro-grid Using DC Fast Charging Architecture*" *Shakeel and Malik (2019)* investigates how Electric Vehicle (EV) batteries can help in micro-grid energy management by storing energy when there is surplus (Grid-To-Vehicle, G2V) and supplying energy back to the grid (Vehicle-To-Grid, V2G) when there is demand for it. Proper infrastructure and control systems must be developed to realize this concept. Architecture for implementing a V2G-G2V system in a micro-grid using level-3 fast charging of EVs is presented. A micro-grid test system is modelled which has a DC fast charging station for interfacing the EVs. Simulation studies have been carried out to demonstrate V2G-G2V power transfer. Test results show active power regulation in the micro-grid by EV batteries through G2V-V2G modes of operation. The charging station design ensures minimal harmonic distortion of grid injected current and the controller gives good dynamic performance in terms of DC bus voltage stability.

- "*Influence of the Electric vehicle battery size and EV penetration rate on the potential capacity of Vehicle-to-grid*" *Liu et al. (2018)* proposes an agent-based model to estimate the real amount of electricity that vehicles can discharge to the grid. Three battery sizes under the penetration rate of 90% and the penetration rate from 10% to 90% were investigated. The results show that the increase of battery capacity led to an increase of V2G potential capacity from 1650.2 kW to 1868.5 kW and that increase from 10% to 90% in penetration rate could account for V2G potential capacity change from 162.8 kW to 1650.2 kW.

- "*Energy-Internet-oriented microgrid energy management system architecture and its application in China*" *Hong et al. (2018)* proposes an Energy-Internet-oriented architecture of microgrid energy management system for China, considering specific technical requirements, markets and policies in China. A case study in China, Beijing Goldwind Industrial Park, is conducted to demonstrate the proposed architecture and method. Simulation results show that by exporting surplus generation to the external customers and bulk power grid, as an important feature of the market dimension of the proposed architecture, the revenue of the microgrid is improved significantly compared to the traditional business mode. Moreover, smart charging of electric vehicles can improve the revenue of the microgrid as well. Finally, the results also show that the proposed method achieves robustness at the cost of lower revenue in non-worst-case scenarios.

- "*Strategic* Energy *Management (SEM) in a micro grid with modern grid interactive electric vehicle*" *Panwar et al. (2015)* investigates energy management in a microgrid with fixed storage (a regenerative fuel cell) and 11 battery electric buses (EVs) using optimisation to minimise line loss, operational cost and maximize the value of stored energy in the fixed cell and EVs simultaneously. Three cases were considered, the first has conventional buses but uses fixed storage and PVs to minimise energy cost using time of day tariffs. The second includes one-way charging of EVs in the microgrid, and the third includes bidirectional (V2G) charging. In all cases, costs were reduced, but the V2G case saved around 10 times the amount of simple energy storage (case one).

- "*Overview of Current Microgrid Policies, Incentives and Barriers in the European Union, United States and China*" *Ali (2017)* comprehensively surveys the policy, regulatory and financial

(economic and commercial) barriers, which hinder the deployment of microgrids in the European Union (EU), United States (USA) and China. In this survey the authors emphasise the need to investigate the feasibility of microgrid policies, regulations and incentives which affect the acceptability of microgrids as a power system. If the policies and regulations can be addressed, microgrid implementation can rapidly move forward. The currently intertwined regulatory and policy barriers are impeding microgrid deployment, so further research into the regulatory frameworks to entice distributed and renewable power producers and stakeholders is needed to support increased microgrid deployment.

− *"Business innovation and government regulation for the promotion of electric vehicle use: lessons from Shenzhen, China" Li et al. (2016)* analyses the role of business models and government regulation in the national pilot program TVTC (Thousands of Vehicles, Tens of Cities). This paper focuses primarily on the government-enterprise cooperation model used in the public transport sector of bus and taxi fleets. It notes that the integration of enterprise business models and government regulations is a significant factor in the promotion of electric vehicles, and in this case bus and taxi fleets were commercially successful. Further suggestions from the paper include encouraging private investment in charging infrastructure and standardising EV development and production. It further notes a tendency for local governments to favour local EV manufacturers.

− *"Barriers to electric vehicle uptake in Ireland: Perspectives of car-dealers and policy-makers" O'Neill et al. (2019)* explores barriers to the uptake of plug-in electric vehicles (EVs) in Ireland, which lags well behind the adoption rates of neighbouring countries. The article investigates the mismatch between early aspirations, policy and infrastructure interventions and the outcomes achieved. These point to progress being limited by a lack of sustained promotion and awareness-raising around EVs, an over-reliance on fiscal instruments and weaknesses in an incentive regime that has remained static. The study also identifies a steep rise in used diesel vehicle imports from the UK. Policy recommendations include: Zero tax on EVs in line with emissions-based taxation systems (environmental performance); alternatively, giving a higher up-front financial incentive (present bias), but retaining an annual motor tax; promote the use of hybrid vehicles (PHEVs and hybrids) as a transitional option before complete conversion to a zero-emissions market

− "*Power Flow Management of a Grid Tied PV-Battery System for Electric Vehicles Charging*" *Badawy and Sozer (2017)* presents an optimal technique for power flow in a PV-battery powered EV charging station. The system includes PV, battery and AC to DC input from the electricity grid, with DC loads including the EV. System management includes two stages for optimisation: Offline Heuristic Optimisation using Particle Swarm Optimisation, and Online Dynamic Programming (DP), in conjunction with a centralised controller. The first processes data to forecast the proceeding 24 hour period for accurate grid tariff forecasting, and to assign an optimal state of charge to EV batteries every hour, calculated by the second process, DP. The model considers dynamic grid tariffs and battery degradation cost. Iterating the experiment, the system converged to a minimum (optimal) price for electricity.

− *"Why Did Better Place Fail?: Range anxiety, interpretive flexibility, and electric vehicle promotion in Denmark and Israel" Noel et al. (2016)* investigates the failure of Better Place, which had a well-conceived business model to encourage electric vehicles. Despite substantial funds, Better Place declared bankruptcy. The paper identifies several reasons Better Place failed in Denmark,

Israel, and in general. They conclude a confluence of social, technical, political, and environmental factors precipitated the demise of BP. These factors cut across environmental attitudes and resistance to change among users, mismanagement and strategic blunders involving corporate strategy, and higher than expected capital costs for vehicles. The authors also suggest that range anxiety may not be a functional barrier to electric vehicle adoption, and may instead be an excuse given by consumers to refrain from changing their behavior, identity, and desires regarding ownership of a vehicle.

– *"Techno-Economical Model Based Optimal Sizing of PV-Battery Systems for Microgrids"* (Bandyopadhyay *et al.*, 2020) this paper investigates optimally sizing a PV system and battery to maximise self-sufficiency, grid relief, while accessing tariff incentives using a comprehensive optimisation model for the sizing of PV, battery, and grid converter for a microgrid system considering multiple objectives like energy autonomy, power autonomy, payback period, and capital costs. The model is applied to two residential load profiles in the Netherlands and Texas to investigate the effect of meteorological conditions on the relative size of PV and battery. Based on the optimisation results, rules for optimal system sizing are derived to facilitate microgrid design engineers during the initial design phase.

– *"On the optimal sizing of batteries for electric vehicles and the influence of fast charge"* *Verbrugge ety al. (2018)* investigates a customer adaption cost that decreases with battery energy capacity. Cost is based on the customer needing alternative transport if EV range is not sufficient. Two emerging technological pathways are compared: fast-charge-capable batteries versus batteries with much higher energy densities (and specific energies) but without the capability to fast charge. For the parameters chosen, fast-charge of a conventional lithium-ion battery offers superior value to the customer relative to the high-energy density cell.

– *"Optimal energy management strategies for the electric vehicles compiling bibliometric maps"* *Raboaca et al. (2012)* presents analysis of the management strategies in the literature to identify the main research directions for optimal energy management strategies.The principal factors for increasing the performance of a strategy are identified are optimization, efficiency, degradation, fuel economy, and systemic development. The authors identified 127 energy management strategies in the studied articles, of these 21.59% have increasing vehicle efficiency as a goal, 10% have fuel economy, 7.8% have hydrogen consumption strategy, and 6.29% work towards performance optimisation and emission reduction.

– *"A review on optimal hybrid technologies, configurations, and applications"* *Shaihk et al. (2021)* provides a comprehensive review of microgrid adopted technologies, control methods, existing applications, software tools, and AI techniques. The review also outlines the techno-enviro-economic assessment and global investment in development and deployment of microgrid projects. The paper makes few conclusions but is valuable as it outlines all actors, technology components and classifies grids and microgrids clearly.

– *"Pareto optimality in cost and service quality for an Electric Vehicle charging facility"* *Woo et al. (2021)* examines the problem of planning an Electric Vehicle (EV) charging facility that provides a high quality of service in charging EVs and incurs a low cost to the facility manager. This problem is challenging because a facility with a larger charging capacity (hence better service quality) can be more expensive to build and operate. The authors propose an optimization model to size an EV charging facility that minimises the facility cost and guarantees a high quality

of service. To reduce the cost further and negate the cost increase from quality service quality, they adopt demand management strategies. Demand management strategies, such as charger scheduling are found to effectively reduce capital and operation cost while maintaining a high quality of service for EV owners.

– *"Optimal operational planning of scalable DC microgrid with demand response, islanding, and battery degradation cost considerations"* (Zia, Elbouchikhi and Benbouzid, 2019) considers a grid-connected DC microgrid which consists of a PV system and a Li-ion battery. Incentives are considered which encourage customers to shift load during scheduled grid-tie line maintenance. As optimal operation of DC microgrid cannot be achieved without considering nodal voltages and system losses, network constraints are also included in the proposed model. Results may aid in DC microgrids adoption planning as they replace traditional AC grids in the future. Simulation results confirm that the integration of battery degradation cost and islanding responsive demand response incentives in DC microgrid applications will significantly influence the operating cost.

– *"The influence of electric vehicle charging strategies on the sizing of electrical energy storage systems in charging hub microgrids"*. (Haupt *et al.*, 2020) is motivated by the economic feasibility of micro grids (MGs). It establishes that energy storage systems (ESSs) are essential to charging hub microgrids (CHMGs) and are currently largely stationary, though with the penetration of EVs there will need to be a mix of stationary ESS and mobile EV ESS. This paper claims that current research lacks evidence and guidance on charging strategy influences, hence a method has been generated using mixed-integer linear programming modelling for scheduling decisions of various ESS capacities, and scenario analyses for EV charging and ESS costs. The case of a large projected CHMG near Augsburg Germany is used to demonstrate the investigative methods. Immediate vs controlled pace charging is discussed for different levels of stationary ESS capacity.

- *"Will Your EV Keep the Lights On When the Grid Goes Down?"* (Gerdes, 2018) discusses example of using EVs in cases of power cuts in California and disaster response in Japan during the tsunami and after. The article notes that EV batteries can power an average home for two to four days. It reports that in Japan Nissan keeps a fleet of Leafs ready to restore power in emergencies through partnering with local governments and the private sector. An example was Nissan sending 50 Leafs to Chiba prefecture during Typhoon Faxai using Leaf to Home equipment from Nichicon. The article also lists startups in the vehicle to home market such as Ossiaco, and vehicle to grid startups Fermata Energy and Nuvve. Three California Community Aggregators have issued a solicitation for 30MW of "behind the meter" batteries to help low-income and medically vulnerable customers to maintain power during outages.