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new energy technology, policy & strategy

EV Technical Standards for Grid Operation

Insights for the National Electricity Market

Prepared for the Australian Energy Market Operator

December 2023

enX Disclaimer

This report was commissioned by the Australian Energy Market Operator to explore the need for Technical Standards for electric vehicles (EVs) and electric vehicle supply equipment (EVSE) to support transmission-scale grid operation.

This work is undertaken at a time when the risks to power system operation from EV uptake, and the need for risk mitigation measures, remains highly uncertain. While best efforts have been undertaken, the report is provided as is, without any guarantee, representation, condition or warranty of any kind, either express, implied or statutory. enX does not assume any liability with respect to any reliance placed on this report by AEMO or third parties. If any party relies on the report in any way, that party assumes the entire risk as to the accuracy, currency or completeness of the information contained in this report.

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EXECUTIVE SUMMARY

Background

This study provides an initial exploration of the emerging and potential transmission-scale power system risks associated with growing EV charging loads. It is based on consultation with a range of specialists in EV and EV charger technology and power systems engineering and well as high-level modelling and international literature and case-study reviews.

EV charging is forecast to be one of the fasting-growing loads in the NEM over the coming decades (shown in **Figure 1** below). While in some ways EV charging performance characteristics are common with other electronic loads such as computers and air-conditioners, EV charging is being rolled out in a way that allows advanced load management include remote management and aggregation. Data from the 2022 IASR is used for analyses, therefore conclusions will reflect assumptions made in within this report.

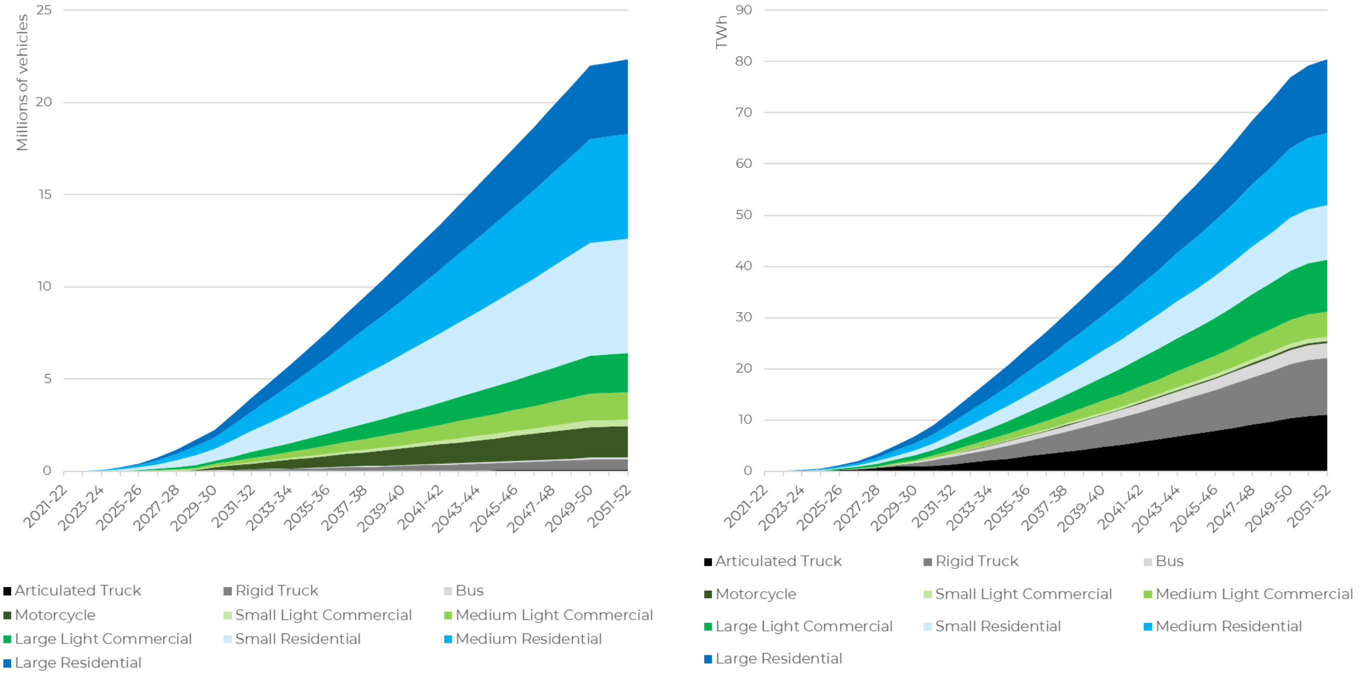

Figure 1 – Forecast BEV numbers and associated annual electricity consumption 2022 to 2052 under AEMO's 2022 ISP Step Change Scenario.

Risk assessment

Our research and consultations indicate that the industry understanding of longer-term power system risks, globally, is at an early stage and is rapidly developing. Most economies remain focussed on addressing local network congestion issues to enable faster EV uptake and better consumer charging experience. A lot of work is also occurring in the development and regulation of interoperability standards to enable smart grid and e-mobility use-cases which are highly relevant to the risk profile of EV charging.

Work on disturbance ride-through performance is at early stages in the UK, Europe and North America. These settings are being considered in the context of a systems approach to EV charging standards, protocols and frameworks alongside smart grid developments.

Like any electronic load, the disturbance ride-through characteristics of EV chargers are not inherent – they need to be programmed in and reflect different product design priorities including product reliability, cost and feature sets. The grid performance characteristics of unidirectional chargers are largely unstandardised and diversity of responses can be expected under different voltage and frequency disturbance conditions.

Overall, we do not expect unidirectional EV chargers to be more vulnerable to voltage and frequency disturbances than other forms of electronic loads, but this needs to be tested as the market grows and evolves over time. Bidirectional chargers are subject to AS/NZ 4777.2:2020 which stipulates the equipment ride-though performance requirements.

While not an intended focus for this study, cyber security and software management risks have emerged as a key area for further consideration and action. This reflects the underlying value of EV charging, as a flexible (and potentially bidirectional) power system resource, that is dependent on communication systems that connect consumers, markets, aggregators, OEMs and other parties. These communication paths create vectors for inadvertent or malicious action that could directly affect the operation of large numbers of EVs at the same time.

Table 1 provides a summary of the key risks identified through this study. These are described in more detail in *Summary of power system risk assessment result* (p 59). These risks are defined in relation to their likelihood and severity in the year 2030-31 and our analysis considers the likely rate of growth of risk over time.

EV charging will be one of the most valuable flexible resources in Australia’s energy transition. Emerging digital technologies and recent market reforms are creating greater scope for EV charging and other flexible loads to participate in wholesale electricity markets. This can occur directly (for customers on a spot passthrough retail tariff), or indirectly through aggregation services whereby BTM demand and generation is varied to manage an electricity retailer’s wholesale market exposure. Both arrangements offer potential benefits to power system reliability and security and can contribute to greater renewables utilisation and lower electricity prices and emissions. As these models become more prevalent, they can also be expected to contribute to greater demand variability, price-demand elasticity, and reduced demand diversity.

However, the price responsive behaviour of EV charging also creates new security risks as sudden load step changes could impact the electricity system’s frequency. These changes could be mitigated by imposing ramp rates or randomised delays on EV chargers. However, the ramp length would need to be punitive (e.g., 5 minutes) to fully mitigate coincident stepping of BTM loads. In effect, if not integrated effectively into market, portfolio and product design, ramp rate requirements could inhibit spot market participation by relevant loads which would run counter to the need to encourage greater demand side participation. Slow ramps and staggered starts could also impact consumer experience and costs for EV charging.

Overall, we consider there is time for Australia to take a strategic approach to risk assessment and mitigation to ensure that approaches are internationally aligned where possible, and at a minimum, nationally consistent. The immediate actions for Australia focus on facilitating collaboration and engagement with local distribution network businesses and in international standards processes to enable two-way knowledge sharing and coordinated action.

Table 1 – Risk assessment summary for 2030.

Type	Description	Assessment	Ratings	Action required
Voltage disturbance	EV chargers disconnect due to a disturbance and the power system experiences a load step, voltage cascade, frequency excursion or instability.	Voltage management is a significant issue. However, EV charging will make a limited contribution to this challenge at scale in the period to 2030.	Low to Medium	Australian Energy Market Operator (AEMO) engage with international efforts to establish ride-through settings for EV chargers and other electronic loads.
Voltage collapse	EV chargers exhibit constant power behaviour due to OEM software implementation of EV-EVSE communications standards.	The constant power characteristic of EV charging load reduces stability and increases the possibility of voltage collapse.	Medium	International engagement to consider requirements for constant current operation for EV charging and other major electronic equipment.
Frequency disturbance	EV chargers represent a significant proportion of system demand and do not provide load relief, resulting in instability and involuntary load shedding.	The lack of load relief, particularly in under-frequency situations, will possibly impact FCAS procurement in the 2030 timeframe.	Medium	International engagement to consider requirements for active power frequency response for EV chargers and other electronic equipment.
Cyber security	CPO, OEM or Aggregator IT infrastructure is compromised, and the power system experiences a very large load step causing widespread power loss.	Cyber threats come in many plausible forms, and the potential to cause a large step up in load at the wrong time represents a very high risk.	Medium to Very High	AEMO continue efforts to support holistic consideration of cyber security risk management and threats.
Software management	A flawed EV charger software patch is deployed, resulting in an error that causes very large load step down and the activation of protection systems.	Errors are possible, and this could have a severe impact with the large market share of some equipment providers.	Very High	AEMO continue efforts to support holistic consideration of cyber security risk management and threats.
Communications loss	The loss of communications for EVSE in a region means smart charging reverts to offline control mode(s) resulting in a very large load step up.	Errors are possible, and this could have a severe impact with the large market share of some technology providers.	Very High	International engagement to consider requirements for EVSE start-up and offline behaviour.

Price response	EV chargers switch on and off repeatedly in response to changes in dynamic pricing, and the power system experience closed-loop price-demand interactions.	The significant financial benefits in price responsive charging makes this likely to exceed frequency control schemes without dispatching.	High	AEMO and industry should consider how market reforms could be designed and implemented to enable a greater share of EV participation.
Event response	EV chargers switch on in aggregate in response to a notice or emergency alert, and involuntary load shedding is required to manage supply and demand.	Akin to customer refuelling their cars before a major storm, this is possible and could have a significant impact on an already strained power system.	High	Network businesses to monitor the impact of weather events, forecasts and market notices on load behaviour.
System restart	EV chargers reconnect to distribution networks after an outage with higher load, which challenges recovery and significantly delays restoration.	Charging load could significantly complicate power system restoration challenges, however these events are rare. Notably, EV provide an opportunity for increased stable load blocks needed for system restoration.	Low	AEMO work with network businesses to monitor load responses to reenergisation after a network outage.
Network management	EV chargers switch on and off repeatedly in response to changes in dynamic operating envelopes, and the power system experiences closed-loop interactions.	Slow and moderate magnitude oscillation from EV chargers on a distribution network constitutes a possible but minor issue at transmission scale.	Medium	AEMO continue work with network businesses and industry to consider system security risks associated with network management.
Diversity destruction	Price responsive EV chargers switch on/off or change charge direction simultaneously in aggregate, and the power system experiences an extreme Rate of Change of Frequency (RoCoF) and/or significant frequency excursion.	EV chargers are likely to switch on or off simultaneously in due to range of incentives/controls, with a major impact on the power system.	Very High	Industry consider ramp rate and/or randomised delay requirements for EV charging and other flexible loads as part of market reforms, portfolio aggregation and product design.

Recommendations

Our research and consultations have arrived at nine recommendations (not in priority order):

- **Recommendation 1:** AEMO should work with Standards Australia to establish formal engagement with ANSI and IEC to coordinate international efforts to establish disturbance ride-through and other inherent device response settings for EV chargers and other major electronic loads.
- **Recommendation 2:** As part of its international engagement, industry should collaborate on the development of requirements for constant current operation and active power frequency response for EV charging and other major electronic loads.
- **Recommendation 3:** AEMO should work towards incorporating disturbance ride-through requirements for EV chargers and other major electronic equipment in the form of internationally aligned and nationally consistent minimum product standards. AEMO should work with DCCEEW to ensure that planned reforms to the GEMS Act 2012 consider its extension to power system security requirements that support Australia’s emission-reduction objectives.
- **Recommendation 4:** AEMO continue efforts to support a holistic consideration of cyber security and software management-related risks for all forms of DER, including security of communications and broader institutional governance and controls for relevant industry participants.
- **Recommendation 5:** Industry should collaborate to establish a program to monitor and share data on localised load responses to a loss of communications and reenergisation after a network outage. This information can inform a more detailed assessment of potential future transmission-scale risks including implications for system restart procedures.
- **Recommendation 6:** As part of its engagement with international standards processes, AEMO should collaborate with network businesses to define desired start-up and offline behaviour requirements for EV chargers and other major electronic loads including data centres.
- **Recommendation 7:** Network businesses should implement an ongoing monitoring program to assess the impact of weather event forecasts and market notices on load changes (e.g., pre-charging of EVs ahead of a storm or price spike) or forecast Lack of Reserve. Monitoring data can be used to assess changes in charging behaviour to inform AEMO load models (minimising load forecasting error) and FCAS procurement.
- **Recommendation 8:** Industry should work with international standards organisations to establish nationally aligned ramp rate and/or randomised delay requirements for EV charging and other flexible loads, balancing system security risk with the need to encourage dynamic demand-side participation.
- **Recommendation 9:** AEMO and industry should consider how market reforms, including the Integrating Energy Storage and the Scheduled Lite Rule Changes, could be designed and implemented to enable a greater share of EVs participating in central dispatch.

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ABBREVIATIONS AND TECHNICAL TERMS

AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
AER	Australian Energy Regulator
API	Application Programming Interface
AS/NZS 4755	Demand response capabilities and supporting technologies for electrical products
AS/NZS 4777.2	Grid connection of energy systems via inverters - Part 2
BTM	Behind-the-Meter
CCS	Combined Charging System
CER	Consumer Energy Resources
CIC	Customer Insights Collaboration
CPO	Charge Point Operator
CSF	Cybersecurity Framework
CSIP-Aus	Common Smart Inverter Profile - Australia
CSMS	Charge Station Management System
DCCEEW	Department of Climate Change, Energy, the Environment and Water
DER	Distributed Energy Resources
DERCF	Distributed Energy Resource Cybersecurity Framework
DERR	Distributed Energy Resource Register
DNSP	Distribution Network Service Provider
DSO	Distribution System Operator
DSR	Demand Side Response
EDNA	Electronic Device and Networks Annex
EFTPOS	Electronic funds transfer at point of sale
EMM	Energy Ministers Meeting
eMSP	e-Mobility Service Provider
ENCRC	Energy National Cabinet Reform Committee
ESA	Energy Smart Appliance
ESB	Energy Security Board
EV	Electric Vehicle
EVIWG	Electric Vehicle Integration Working Group
EVSE	Electric Vehicle Supply Equipment
GEMS	Greenhouse and Energy Minimum Standards
HEMS	Home Energy Management System
IEA	International Energy Agency
IEC 62196	Plugs, socket-outlets, vehicle connectors and vehicle inlets
IEC 61851-1	Electric vehicle conductive charging system
IEEE 1547	Standard for Interconnection and Interoperability of Distributed Energy Resources
IEEE 1901	Standard for Broadband over Power Line Networks
IEEE 2030.5	Smart Energy Profile Application Protocol
IEEE 802.3	Standard for Ethernet
IEFT	Internet Engineering Task Force
IoT	Internet of Things
ISO	International Organization for Standardization

ISO 15118	Vehicle to grid communication interface
ISO 15118-2	Network and application protocol requirements
ISO 15118-20	2nd generation network layer and application layer requirements
Modbus	Client-server communication protocol for intelligent devices
NEL	National Electricity Law
NER	National Electricity Rules
NEVI	National Electric Vehicle Infrastructure program
NEVS	National Electric Vehicle Strategy
NIST	National Institute of Standards and Technology
NREL	National Renewable Energy Laboratory
OCA	Open Charge Alliance
OCPP	Open Charge Point Protocol
OCPI	Open Charge Point Interface
OEM	Original Equipment Manufacturer
OSI	Open Systems Interconnection
OBC	On-Board Charger
PAS 1878	Energy smart appliances system functionality and architecture specification
PKI	Public Key Infrastructure
PLC	Power-Line Communication
RJ45	Registered jack physical network interface for data
TCP/IP	Transmission Control Protocol / Internet Protocol
TLS	Transport Layer Security
UL 1741	Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources
V2G	Vehicle-to-Grid

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1. INTRODUCTION

NEM Engineering Framework

This report relates to the delivery of one aspect of AEMO’s NEM Engineering Framework: to develop fit-for-purpose performance and connection processes for new loads, specifically ensuring that they can withstand disturbances and provide appropriate grid support.

Electric vehicle charging

To AEMO, a high uptake of electrified transport and DER represents a valuable opportunity for consumers to contribute to efficient power system development and operation[1]. As part of the NEM Engineering Framework, AEMO identified a need to better understand the broader landscape and implementation of technical standards and grid connection requirements that apply to Electric Vehicles (EVs), EV Supply Equipment (EVSE) and other potentially significant loads in Australia and internationally.

Grid integration standards for EV chargers

Power system disturbances, like a voltage drop/rise, can trigger EV charging inverters to shut down, and when large group of such loads trip they can impact grid stability. The need to better understand this risk was originally identified by the Distributed Energy Integration Program (DEIP) EV Integration Taskforce. In a 2021 report,[2] the taskforce identified risks associated with EV and EVSE interaction with the grid, particularly in relation to their autonomous or inherent capability, such as disturbance ride-through and grid support functions.

System security costs

With a lack of visibility of EVs/EVSE on the network, system operators may have to operate the power system with larger operating reserves and procure additional grid support services to account for system security risks associated with these assets. This can come at a significant cost that will ultimately pass down to consumers. As a potential alternative, the DEIP report recommended autonomous grid support capabilities of EVs and EVSE equipment be explored to achieve disturbance ride-through and support broader power system security outcomes. To attain such capabilities, the report recommended performance standards be pursued for EVs and EVSEs.

Technical standards for grid integration

The DEIP Taskforce emphasised the important role of standards to address the risk of inefficient integration of EV charging on the grid. It was identified that standardisation of Vehicle to Grid Integration (VGI) requirements may reduce costs associated with capital investment and operational requirements in the NEM. This included a finding that standardisation around communication and information exchange protocols can help in specifying the technical limits of operating EV/EVSEs to maintain grid reliability, security, and power quality.

The importance of international alignment

Original Equipment Manufacturers (OEMs) of EVs and EV chargers design their components to address a range of international customers and relevant technical standards. A unique standard for the Australian context can compromise the availability of those vehicles undermining emission reduction policies and choices for consumers. Australia typically aligns IEC and ISO standards by reference or adoption.

Internationally, various distribution codes have employed standards-based approaches to manage the performance of distributed generation including vehicle-to-grid (V2G). Other international standards such

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[1] AEMO (2023) 2023-inputs-assumptions-and-scenarios-report.pdf (aemo.com.au)

[2] AEMO (2021) *Distributed Energy Integration Program – Electric Vehicles Grid Integration Report*

as ISO 15118, OCPP, Open ADR and IEEE 2030.5 offer standardised communications functions relevant to energy and e-mobility market integration. No regulated international standards have been identified for unidirectional chargers to achieve disturbance ride-through and broader network support capabilities for power system outcomes.

Extension to unidirectional chargers

The Taskforce noted that Australian standards already exist that regulate aspects of disturbance performance and grid response modes for V2G bi-directional chargers, specifically AS/NZS4777.2:2020. This standard is fit-for-purpose for bi-directional chargers and changes to this standard are not the focus of this work. A key question for this project is whether similar or alternative requirements should be imposed on unidirectional chargers.

Relevant charging configurations

Unidirectional charging

In AC charging, EV Supply Equipment (EVSE) provides AC power to the vehicle. An On-Board Charger (OBC) module inside the vehicle converts this to DC power, which in turn charges the vehicle battery. Power flow to and from the battery is regulated by a Battery Management System (BMS), which is essential for the safe and sustainable operation of the energy storage system. In DC charging, the EVSE provides DC power directly, which enables higher power transfer as it bypasses the power limitations of the OBC. Regardless of format, the session requires two-way communication between the EV and EVSE to coordinate a safe and efficient charging session.

Bidirectional charging

The bidirectional charging configuration of most interest to the NEM is V2G. In this case, power available from the EV battery is used to supply electricity to a distribution network for a range of services such as wholesale market supply, network support or provide Frequency Control Ancillary Services (FCAS). A DC Vehicle-to-Grid (V2G) architecture is expected to be attractive in markets like Australia where there is a high prevalence of small-scale embedded generators. In this case, the EV (via a suitable EVSE) can supply DC power to a hybrid inverter that is also connected another DC power source such as solar panels or a battery energy storage system (BESS). Alternatively, the EVSE can convert DC from the vehicle to AC on the premises. In either case, the power conversion to AC is achieved outside of the vehicle by a grid code compliant inverter.

While AC V2G operates in much the same way, the power conversion in AC V2G is achieved with a grid code compliant inverter within the vehicle. This capability is provided by the vehicle’s OBC and regulation in this space is evolving.

Smart charging

Both unidirectional and bidirectional charging can benefit from the management of charging profiles, to meet both transport energy, financial and grid integration objectives – for example, having enough range for driving and minimising the cost of a charging session.

Charge optimisation may occur locally or remotely. On a residential customer premises, EV charging may form part of an integrated home energy management system (HEMS), optimising other Behind-the-Meter (BTM) resources for self-consumption or market participation. Remote management may include communication with a distribution system operator (DSO), to receive dynamic operating envelopes using CSIP-Aus (an Australian adaptation of IEEE 2030.5). A Charge Station Management System (CSMS) may be located locally or remotely to communicate with the EV charger via the Open Charge Point Protocol (OCPP).

Figure 2 below provides a simplified visual representation of possible charging configurations.

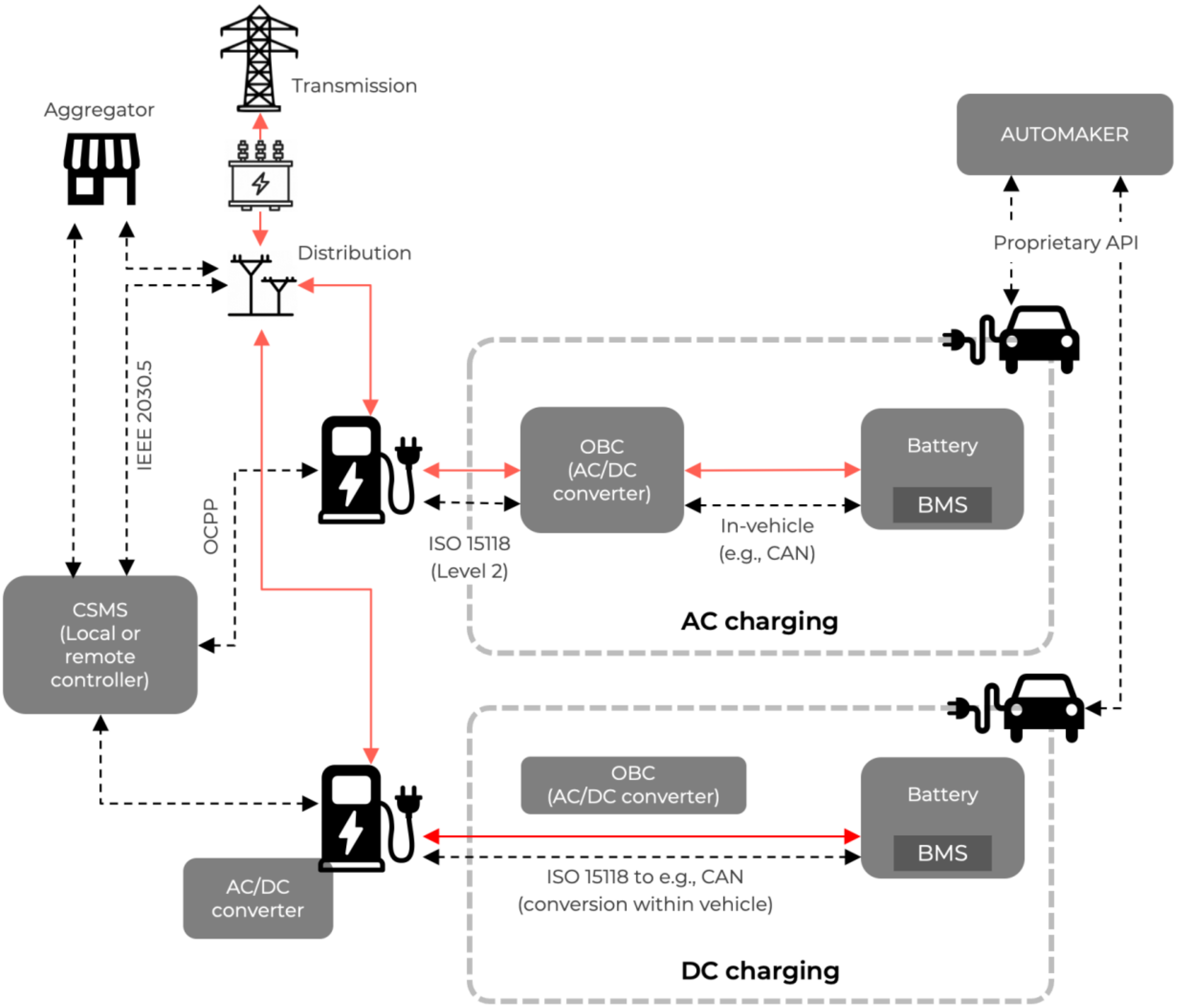

Figure 2 – Simplified architecture for AC and DC EV charging. Red lines represent AC or DC power flows, black lines represent communications and control signals.

Document structure

This report aims to define and prioritise risks that may be associated with Australia's growing EV fleet, whilst also considering the landscape of current and proposed technical standards, grid connection requirements, and compliance frameworks that apply to EV, EVSE and other potentially significant loads in Australia and internationally. The report is based on consultation with world-leading experts to draw actionable insights and define what additional measures are required to support system security outcomes as our vehicle fleet electrifies.

This document is structured as follows:

- Types of loads
- International review
- Relevant standards
- Compliance frameworks
- Potential risks to system security
- Recommendations for the NEM

Types of loads

The purpose of this section is to provide a high-level materiality assessment of specific power system risks associated with major load types, including the impact of inverter-based loads on the dynamic behaviour of power systems. Focusing on system security, this aims to identify and characterise key gaps that are not sufficiently addressed in work to date. It focusses on loads that may form a large proportion of total instantaneous system load at certain times, and any technical standards that might apply to those kinds of loads in Australia.

International review

The purpose of this section is to identify and summarise insights from relevant international power systems regarding system security risks associated with high EVs/EVSE penetrations, and relevant work by other international organisations. The focus of this work is jurisdictions and networks experiencing or forecasting system security challenges related to EVs/EVSE.

Relevant standards

The purpose of this section is to identify any technical standards that apply to EVs and EVSEs sold in Australia (specifically the DC to AC inverter) that include specification of how the device interacts with the grid in unidirectional and bidirectional charging operation. The focus of this work is on behaviours relevant for system-wide power system security, including:

- Capabilities
- Frequency/voltage protection settings
- Anti-islanding protection
- Frequency response requirements
- Ramping limits
- Measurement accuracy requirements

Compliance frameworks

The purpose of this section is to map out the compliance and conformance processes that could be used to ensure that EVs and EVSEs sold in Australia deliver requirements defined in standards. The focus of this work is identifying which parties are responsible for roles including:

- Defining standards
- Testing devices against those standards

- Determining which devices meet those standards and therefore can be sold in Australia, and maintaining a register/list of approved products
- Accrediting installers
- Confirming that new installations have been completed correctly in accordance with standards
- Monitoring compliance with standards over time
- Incentives/penalties to support enforcement.

This analysis aims to provide insights and/or evidence (if possible) on whether it appears that these roles are being delivered successfully at present and identify any known or suspected gaps in these compliance and conformance processes.

Potential risks to system security

The purpose of this section is to assess potential risks to system security that may occur from a growing number of EVs and EVSE in the NEM. The focus of this work is to identify potential electrical designs and communications architectures, including aggregations, that may create system security risks at sufficient penetrations.

Recommendations for the NEM

The purpose of this section is to summarise the main insights from our research for the NEM. This includes recommendations related to the possible options and pathways to incorporate grid technical settings and functionality (such as disturbance ride-through) as part of EV/EVSE design, manufacture, point of sale.

2. SUMMARY OF LOAD TYPES AND THEIR IMPLICATIONS

Electricity consumption in the NEM vary continuously from milliseconds to hours (operational timeframes) to seasons and years (planning timeframes). A central operational requirement for the NEM is to always keep supply and demand in balance, to ensure system frequency is kept with the Normal Operating Frequency Band (NOFB) of 50Hz +/- 0.15Hz.

This is principally achieved by dispatching generation to meet forecast demand in every 5-minute trading interval, and through frequency regulation services whereby AEMO instructs market participants to increase or decrease generation or load to keep them in balance *within* each trading interval. AEMO also procures contingency frequency response services to help manage frequency excursions. The resilience of power system frequency to sudden changes in supply and demand balances is closely associated with the levels of primary frequency response and system inertia which can be provided by generation and load resources.

Large industrial loads, such as pumped hydro and smelters, are typically notified to AEMO by market participants and can be subject to operation information sharing and scheduling requirements. Future requirement for large loads, including in relation to disturbance ride-though, are being considered through the *AEMO review of technical requirements for connection*.[3]

Smaller loads are typically not visible to AEMO and have not traditionally been considered material to the maintenance of system frequency. This assumes smaller loads will not run at full capacity at the same time, and small load changes tend to balance each other out, producing a relatively smooth aggregate load profile (i.e., load diversity).

Changes in the characteristics of load in the NEM, and its manner of control, create an imperative for AEMO to consider the way loads may interact with power system operation across all timescales. Clause 4.2.5 on the National Electricity Rules (NER) requires AEMO to consider the capabilities of all equipment involved in generating, utilising or transmitting electrical energy.[4]

This chapter provides a high-level overview of electrical load changes, and their characteristics, in the residential and commercial sectors. While industry loads are also highly significant, their generally bespoke nature, and limited publicly available information, means they need to be considered outside of the scope of this study. This analysis is intended to provide context for the study's focus on EV loads, rather than providing a definitive analysis of other load types. In general, there is currently a lack of publicly available information on residential, commercial and industry load changes and this may need to be addressed through additional work.

General load types and characteristics

Loads have different technical characteristics that affect the way they interact with the power system, affect power quality, and respond to frequency or voltage disturbances.

From a circuit perspective, loads are defined by their impedance and can be classified as:

- **Resistive** – Load's that convert electricity directly to heat are usually resistive. Examples include resistive water heaters, electric ovens, and incandescent lamps. The current flow is in phase and proportional to the instantaneous voltage, so the power factor Is unity.
- **Inductive** – Loads can present an impedance which include an inductive part due to the presence of large coils or windings. The typical example of this is motor loads and associated equipment, where the motor is connected to the power system directly, rather than via a power converter. Older compressors, refrigerators, air conditioners and power tools fall into this category. In the presence of an inductive load, the phase of the current lags the voltage. Reactive power is

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[3] AEMO (accessed 13/7/2023) *AEMO review of technical requirements for connection*

[4] National Electricity Rules, Clause 4.2.5 (accessed 12 July 2023) *Technical envelope*

'consumed' resulting in a lagging power factor. A lagging (or leading) power factor is undesirable as it results in system losses.

- **Capacitive** –Electrical circuits that can have a combination of resistive, inductive, and capacitive characteristics. Purely capacitive loads are uncommon. While capacitive loads can also be used for power factor correction, the capacitive components discussed here are for harmonic filtering in electronic circuits. In the presence of a capacitive loads, the power factor is 'leading'.
- **Non-linear** – Non-linear loads produce harmonic currents which can trigger network protections at a local level and contribute to losses in the power system. Equipment examples include arc discharge devices such as fluorescent lamps and electric welding machines, and DC devices supplied via a rectifier and capacitor.

For the purposes of this study, we also classify loads as either:

- **'Analogue' loads** – In this study, these can be understood as loads that have technical characteristics directly associated with the process of converting electricity into the end-use application such as light, heat or motion. Examples include simple toasters, kettles, water heaters, many pumps, and fans. Analogue loads are characterised by continuous and inherent performance related to the underlying physics of the power consuming load, and the absence of electronic power conversion.
- **Electronic loads** – Electronic loads make use of an electronic power conversion circuit between the AC input and the end-use application. Examples Include LED lighting, induction hobs, and EV chargers (EVSEs). Most modern electronic appliances found in home or business are electronic loads, including all devices that require DC, such as laptops. Current product legislation mandates that higher power loads have a power factor near to unity and produce low levels of harmonic current. This has resulted in some reactive loads, such as motors, being connected via electronic power converters which can ensure unity power factor, improving system efficiency. Examples include modern air-conditioners and variable speed drive motors on power tools. Power converters are designed to reflect specified design objectives related to equipment function, equipment protection and regulatory requirements. The response of electronic loads to grid frequency or voltage disturbance is therefore highly dependent on the power converter design.

Power modes for electronic loads

The response of electronic loads to frequency or voltage disturbances can typically be described by one of the following operation modes:

- **Constant impedance/resistance mode** – Within each AC cycle electronic loads behave resistively. The current is linearly proportional to the input voltage as required to achieve unity power factor. However, during voltage excursions, such as sags and swells, electronic loads may enter other operating modes to support the desired operation of the device.
- **Constant power mode** – The power supply in many devices maintain a constant voltage output for small voltage or frequency disturbances. IT equipment such as PCs and TVs, where the constant DC output voltage characteristic stops the screen getting lighter or darker as the AC voltage varies. This results in the product taking constant power, independent of the AC line voltage. Battery chargers for electric vehicles and stationary batteries will often use a process of constant current (CC)/constant voltage (CV). It is however important to realise that the CC/CV description related to the connection from charger to battery. Viewed from a grid perspective these loads are constant power, maintaining a constant power to the battery for a small voltage or frequency disturbances.
- **Constant input current mode** – The device consumes current equal to the programmed current setting regardless of the input voltage. Equipment examples include LED loads which apply this for circuit protection. Constant current mode therefore provides a dampening effect on voltage excursions.

Electronic loads are generally insensitive to frequency variation, with many devices designed to operate 45 to 65 Hz at constant power, to support use in a wide range of international markets.

The power mode of an electronic load has a material bearing on how the load responds to power system changes including voltage and frequency fluctuations. For example, changing the voltage of a distribution network can affect real-time, real power consumption for devices such as resistive electric water heaters. This effect can even be utilised by networks to provide frequency response services.[5] An electric vehicle charger in a constant power mode would not respond to changes in network voltage in this way, as the charger would adjust input current to ensure a constant power draw as per the current charge rate setting.

Switched mode power converters in electronic loads can be designed to operate at high (millisecond) resolution to approximate the continuous and inherent performance characteristics of analogue loads. A high-tech example of this is a grid forming inverter performing AC/DC/AC power conversion for BESS which, during a load or generation cycle, can emulate the characteristics of a synchronous generator or motor providing inertia and strengthening local voltage waveform stability. Achieving such performance characteristics for electronic loads requires more sophisticated design and power electronics components which adds cost to equipment design. Power electronics design for equipment such as grid forming inverters are currently the subject to continuing innovation, which is likely to lead to cost reductions, and more capable equipment supplies over time.

Load control modes

Electronic and analogue loads can be also broken down by the way they are controlled and respond to market or power system or other conditions. For the purposes of this study, we talk about:

- **Manual control** – Different parts of the power system require physical intervention by a human to change its operation. Examples of this are light switches, toasters, or manual tap changes on a distribution transformer.
- **Automated or inherent control** – Equipment can be automated to respond to specific external conditions using ‘physical’ or digital controls. Examples of this include streetlighting, or a timer or a thermostat on a water heater. More sophisticated examples include inverters programmed for volt-var or frequency-watt responses.
- **Application or remote control** – Equipment can also be set up with software to respond to or participate in an energy market. For example, a smart EV charger set to respond to the change of an electricity retail or wholesale price band. This may involve a third-party agent through an energy management system or CSMS. This utilises communications systems and protocols locally or remotely (e.g., via the internet). Examples of this include batteries participating in an electricity spot market, or an appliance operated by a DNSP under a load control tariff arrangement.

From a power system risk management perspective, remotely controlled equipment can have an increased likelihood of responding to real-time market price signals (or other conditions) in a coincident manner (i.e., reducing diversity). While price responsiveness (demand side participation) is essential to improving system utilisation and reducing costs, the use of internet communications also creates inherent cyber risks that could undermine power system security outcomes.

In practice, these control modes often overlap. Automated responses can be subject to manual override, or firmware updates can be delivered by an OEM over the internet. End-user behaviour also impacts the operation of automated and remotely controlled equipment both in real time and over planning and investment timeframes. It is, however, useful to contrast these different control modes when exploring the risk associated with different load types operating for different purposes, and in different ways.

NEM load forecasts

The makeup of loads in the NEM changes over time due to structural changes in the economy and the uptake of different technologies and practices by businesses and consumers.

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[5] United Energy (2020) *Voltage Controlled Frequency Regulation System Final Report*

AEMO's *2022 Statement of Opportunities* sets out three scenarios that describe incremental changes in aggregate operational ('sent out') demand (GWh), and a Hydrogen Export scenario that describes a six-fold increase by 2050[6] (see Figure 3). Under the Progressive Change scenario, aggregate demand is forecast to increase 117% from 2023 levels, while summer peak demand increases by around 50% over the same period.[7]

These scenarios do not fully incorporate electrification of the kind required to achieve global emissions reductions goals and we understand AEMO is currently considering more ambitious electrification scenarios in the context of the 2024 ISP. The 2023 Gas Statement of Opportunities forecasts only a modest reduction in aggregate annual gas consumption (26%) by 2050.[8]

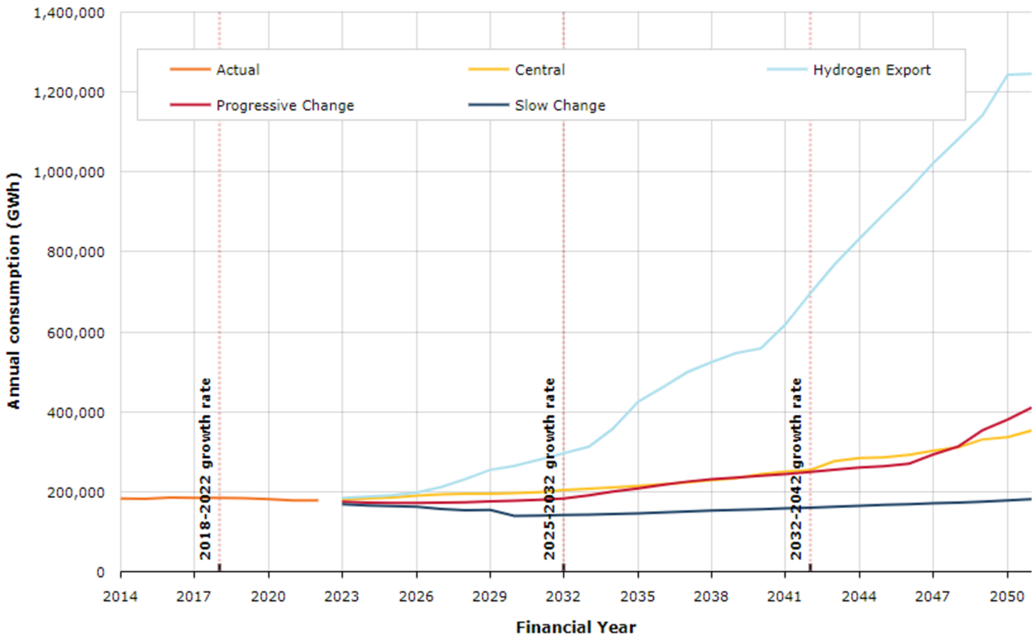

Figure 3 – Electricity Annual Consumption Operational (Sent-Out) forecasting scenarios (ESOO 2022)

Residential sector loads

As shown in Figure 4, The *2021 Residential Baseline Study 2000- 2040*, commissioned by the Australian Government, indicates virtually no change in residential load composition to 2040, when excluding solar uptake and transport electrification. At this level of reporting, there appears to be a limited overall impact of the expected electrification of water heating, space heating or cooking, or the potential shift from resistive electric to heat pump and induction cooking technologies. The associated *Methodology Report*[9] indicates these trends may be potentially observable in the underlying data model however, with available data, it is not possible to determine the likely breakdown of residential load by power mode or control mode.

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[6] AEMO (accessed 12 July 2023) *Electricity Annual Consumption Operational (Sent Out)*

[7] AEMO (accessed 12 July 2023) *Electricity Maximum Demand Operational (Sent Out)*

[8] AEMO (accessed 12 July 2023) *Gas Annual Consumption Total*

[9] EnergyConsult (2020) *2021 Residential Baseline Study for Australia and New Zealand for 2000-2040* - *methodology_report.v1.3.pdf*

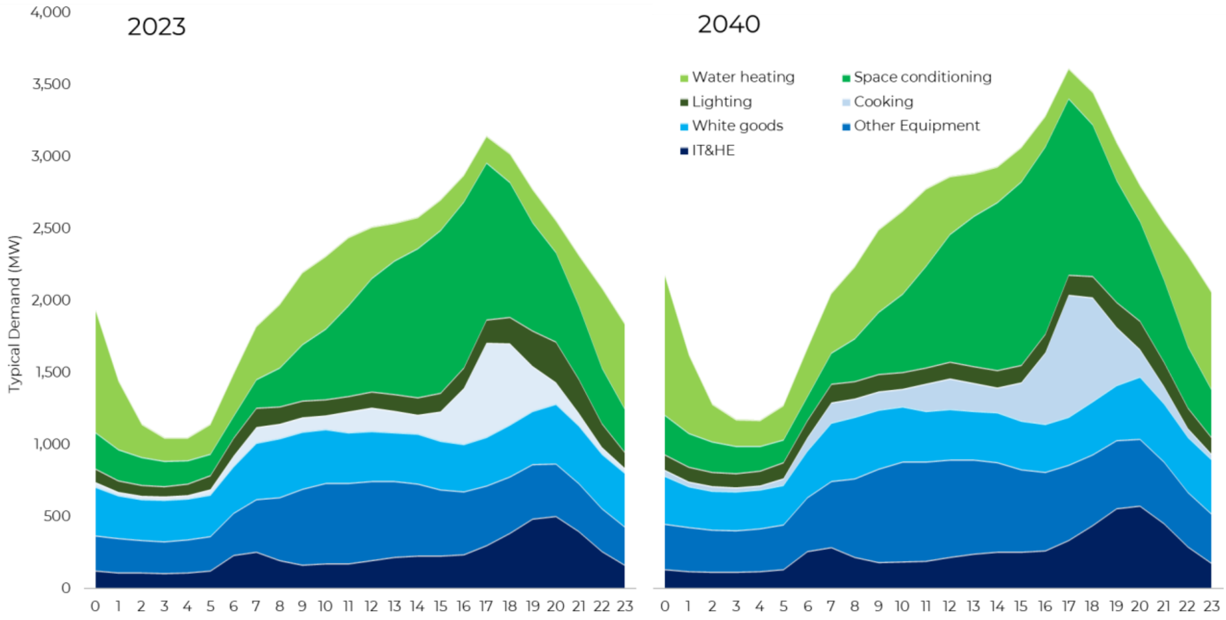

Figure 4 – Average daily end-use electricity consumption in the residential sector in NSW for 2023 vs 2040[10]

Through our work with technology providers, enX is observing the following trends in residential energy using equipment:

- **A continued shift to LED lighting** – While already dominant in most residential lighting applications, LED lighting is likely to continue to replace incandescent, halogen and compact fluorescent lighting due to energy efficiency and performance advantages.
- **The incremental replacement of gas and resistive electric water heaters with heat pumps and resistive heaters on timers or load control (DNSP load control or HEMS control)** – Electric water heaters will increasingly make use of electronic controls and the interest of customers in solar self-consumption is likely to continue the current trend of reductions in the number and aggregate capacity of water heaters under DNSP direct load control.
- **Growth in reverse cycle air-conditioning and heat pump hydronics** – Heat pump technology is developing significant cost advantages for space heating and is being supported by gas replacement policies and incentives across various jurisdictions.[11]
- **A growth share of induction and resistive cooking (cooktops and ovens, respectively)** – This is already being driven by government policies that limit gas connections in new residential areas.
- **Incremental growth in consumer electronics** – While the stock of consumer electronics is likely to grow, continuing improvements in device energy efficiency will mitigate overall load growth in this category.
- **Growth in third party control of residential energy using equipment** – Innovations in HEMS and virtual power plant services are likely to increase the scope of appliances and equipment under third-party control. Major equipment classes brought under third party control include pool pump and heater controllers, water heater and other semi-flexible loads.

Long term equipment trends in the residential sector are subject to consumer product and service preferences and product development by international OEMs. For example, there is a clear trend by inverter manufacturers and HEMS providers towards more integrated products and services, bring a wider range of end-use appliances and generation equipment under control. Locally and internationally, there is divergence in business models with OEM's progressing both cloud-based and site-based control

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[10] Ibid – Adapted from *power_demand_by_time_of_use_data.xlsx (42.67mb)*

[11] Research on air-conditioners responding to different frequency excursions identified the need to update power system study methodologies to better take account of inverter-based frequency ride-through characteristics. Bai F. et al (2020) *Extraction of Dynamic Frequency Response Characteristics and Modelling of Modern Air Conditioners*

architectures. These have different advantages and vulnerabilities, and the future evolution of consumer services will depend on the extent to which Australian smart-grid architectures promote site-level conformance (e.g., for market participation or dynamic operating envelope compliance) and equipment interoperability standards (which allow for multiple equipment types and brands to be brought under third party control).

Commercial sector loads

In 2020, AEMO engaged DeltaQ to assess the proportion of commercial loads that related to different load types (e.g., large motors, small motors, power electronics, etc.) and ANZSIC (industry) code. Load profiles were developed as an input into AEMO PSSE and PSCAD models, which underpin many of AEMO's critical functions and are used to understand the way the power system behaves during disturbances, to inform AEMO's operations.[12] The DeltaQ report provides a high-level break down of the contribution of major commercial sector load types. As shown in Figure 5, electronic loads are estimated at around 40% of total peak load in NSW in summer.

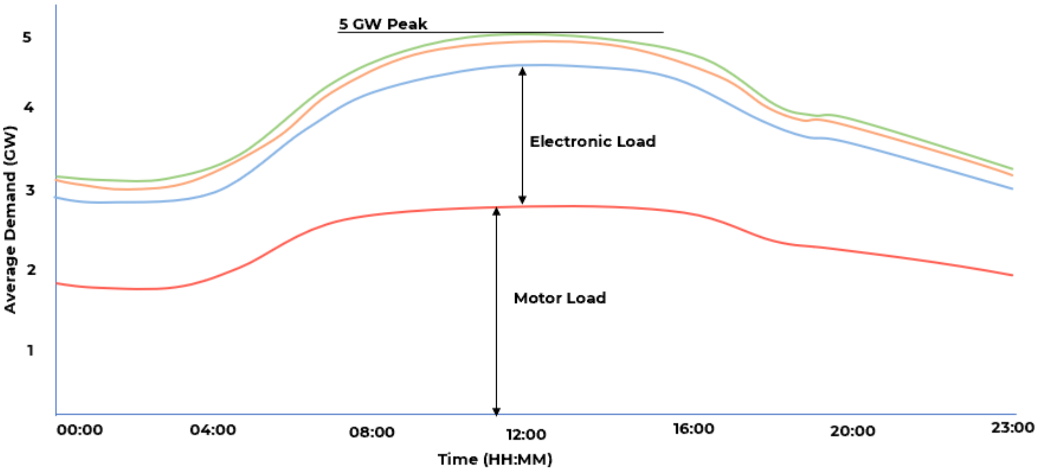

Figure 5 – Load profile showing the emerging prominence of electronic loads in NSW on a summer weekday. *Adapted from: DeltaQ (2020) AEMO Commercial Load Model – User Guide*.

The DeltaQ analysis was based on current estimated loads, rather than forecasting over the long-term timeframes relevant to this current study. Consistent with the project scope, it did not include an analysis of potential long-term growth in data centres or associated UPS loads, or commercial sector trends such as heat pump loads replacing electric and gas boiler units in commercial buildings or induction cooking in hospitality industries.

There is limited data collected or published on likely economy-scale changes in commercial sector electricity end-uses in Australia which makes it hard to forecast future, trends. Overall, given broader economic, policy and societal trends, it is prudent to account for the following potential changes in commercial loads:

- **Continued shift to LED lighting** – LEDs will continue to replace of fluorescent and other lighting technologies due to cost advantages and building energy efficiency minimum performance requirements.
- **Incremental replacement of gas and resistive electric boilers with heat pumps** – Heat pumps are becoming the most economic choice for commercial space and water heater applications, driven by cost and emission reduction objectives.

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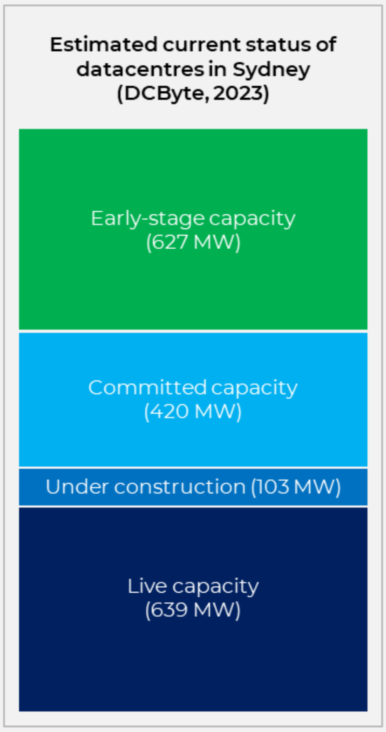
[12] DeltaQ (2020) *AEMO Commercial Load Model User Guide RevB*

- **Growth in induction and resistive cooking (cooktops and ovens)** – While not yet as pronounced as in the residential sector, we can expect a substantial shift away from gas for commercial cooking applications, driven by cost and emission reduction objectives.
- **Growth in air-conditioning loads** – Population growth and climate change will drive up energy demand for air-conditioning however this may be mitigated by energy efficiency improvements in equipment, operational practices (e.g., load shifting) commercial building design.
- **Substantial growth in data communication and processing energy loads** – Based on international estimates, data centres account for around 1% of global electricity demand with strong forecast load growth forecast. This is described further in the breakout box below.

Data centre load growth

In 2018, data centres were estimated to account for approximately 1% (or 205 TWh) of global electricity demand. By 2030, this is estimated to grow to between 1,100 and 8,000 TWh with varying modelling assumptions. While the demand for online data services is pushing up demand, substantial efficiency gains are also being achieved with processor efficiency improvements, reductions in idle power, increased storage drive density and slowing server growth.[13]



Market analysis by DCByte indicates data centre energy peak loads in Sydney could grow from 639 MW to over 1,400 MW with projects currently planned or under construction.[14]

Data centres are large concentrations of electronic loads (computer servers) with backup power systems called uninterrupted power supplies (UPS). These often combine batteries with diesel generators and in some cases rotary UPS systems (flywheel-style spinning reserve) to allow for fast response and backup power in the event of grid failure.

A 2021 report by CSIRO[15] recommended that AEMO should further investigate the current state of the sector and its recent trajectory and pursue knowledge sharing between data centre operators, energy network businesses, AEMO, government and the research community. CSIRO was unable to estimate or forecast data centre electricity demand in Australia.

These power systems can look like large industrial loads, where the system has BTM control allowing import and export of power as needed, only limited by performance and grid connection requirements, and the design of protection systems.

Load relief is practicable for loads where they can vary their power with a small impact on performance (E.g., EV chargers, heating/aircon, hydrogen electrolysers). It is likely that data centres may be far more reluctant to provide load relief. Some data centres are constant power loads without fault-ride through capabilities. This is a significant concern in the US as data centres behaving as this can exacerbate the impact faults on power system frequency and voltage.

The CSIRO noted the scale of individual data centres is also rapidly increasing with ‘hyperscale’ facilities (some well over 100MW peak) potentially accounting for nearly half of total data centre electricity consumption globally. While larger data centres are typical more efficient, they present a more concentrated risk profile in relation to sudden grid disconnection.

The National Australian Built Environment Rating System (NABERS) has a set of voluntary assessments that provide an indication of the operational energy efficiency and environmental impact’ of a data centre. Given the significant growth potential of data centres, and their implications for power system planning and operation, there may be a case for considering mandatory disclosure of datacentre standing data, potentially under a DER Register-type reporting framework[16].

Electric vehicles

AEMO’s 2022 ISP step change scenario forecasts over 22 million electric vehicles will be charged from the NEM by 2050, with associated annual electricity demand growing to around 80 TWh over the same period.

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[13] Energy Post (2020) *The nexus between data centres, efficiency and renewables*
[14] DC Byte (2023) *Everything About Data Centres*
[15] CSIRO (2021) *Data Centres and the Australian Energy Sector*
[16] AEMO (accessed 12 July 2023) *Distributed Energy Resource Register*

From a current base annual NEM demand of just under 200 TWh, this represents a 40% increase over the next 30 years.

As shown in Figure 6, residential vehicles constitute 71% of final vehicle numbers but only 47% of load. Commercial vehicles represent 18% and 20% of vehicle number and EV charging load respectively. Heavy vehicles, such as truck and busses, represent only 3% of vehicle numbers, but 31% of annual EV charging load. Motorcycles are forecast to represent less than 0.6% of annual EV charging load in 2052.

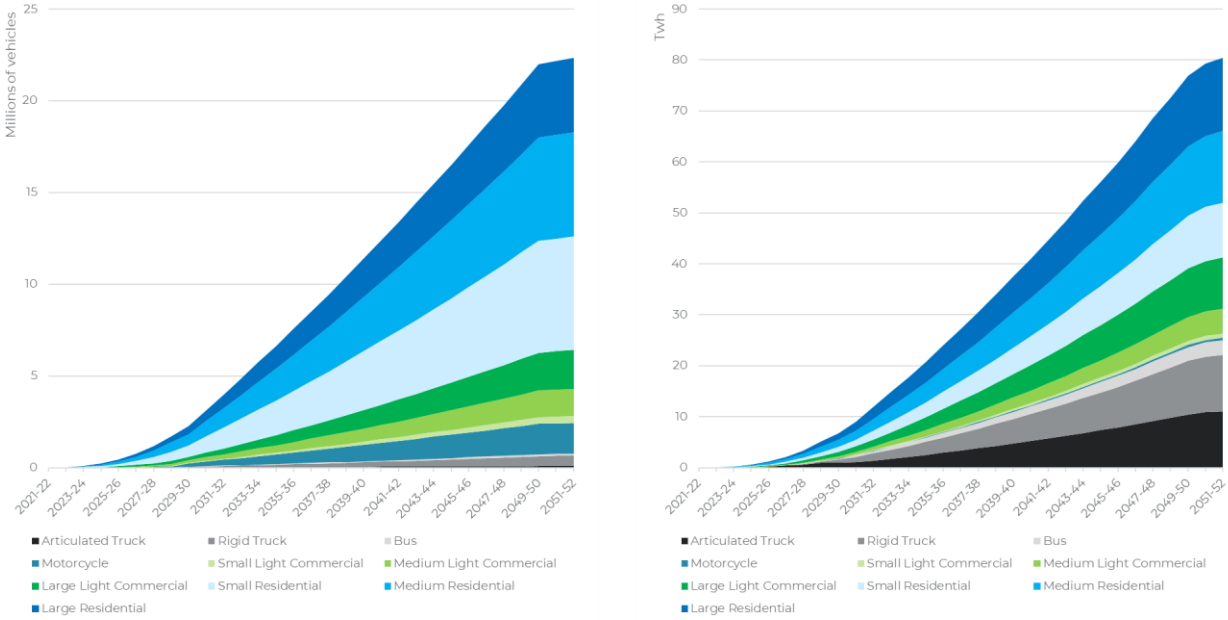

Figure 6 – Forecast BEV numbers and associated annual electricity consumption 2022 to 2052 under AEMO's 2022 ISP Step Change Scenario.

The underlying charging technology is not substantially different between vehicle classes and the power system characteristics of different charging modes are explored further in Chapter 3 below, along with an analysis of associated power system risks.

The only load that is currently forecast to grow at a comparable rate to EV charging under AEMO's 2022 ISP is hydrogen electrolysis (though only under the specific Hydrogen Export scenario) and, potentially, data centres. The very high expected growth of EV charging, and uncertainties about its technical performance characteristics, is the reason for this study.

End-use equipment testing results

A report by the Australian Power Quality Research Centre (APQRC), University of Wollongong Australia in partnership with other Australian organisations, presents insights into load responses to grid disturbances.[17] This includes the response of power electronics and inverter-based loads connected to distribution networks to various voltage, frequency, and phase disturbances via extensive testing.

Three inverter-based air-conditioning units tested exhibited unique behaviour under the same faults due to their own distinct protection and control mechanisms. The tested units maintained normal operation throughout all the tests in relation to frequency and phase angle jumps, however disconnected under voltage sags between 0.5-0.3 pu depending on the duration of the disturbance. Two AC EV chargers were tested with a Nissan Leaf EV, which showed some similar behaviour to inverter-based air-conditioning units.

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[17] APQRC (2023) GPST DER and Stability Stage 2 Final Report

The IEC 61851 Mode 2 (‘trickle’) AC charger was able to ride through all disturbances down to a voltage sag of 0.6 pu, then disconnected for voltage sags of between 0.5-0.3 pu depending on the duration. The severity of the disturbance, in magnitude and duration, was found to impact the disconnection time. For a 0.5 pu sag of 120 ms the charger disconnected for 7 seconds, but for a 0.3 pu sag of 80 ms the charger disconnected for 32 seconds. No significant impacts were observed during voltage swell, phase angle jumps, or frequency disturbances.

By contrast, an IEC 61851 Mode 3 (‘Wallbox’) EV charger successfully rode through all disturbances without disconnection. The charger did show a momentary decrease in active and reactive power during a sag, but resumed charging once the nominal voltage was restored. During swell the charger did not exhibit any interruption, however the EV charging system responded like a constant power load, meaning its current reduced in proportion to the voltage rise. Ride-though is a result of both EV OBC and EVSE performance.

Overall load trends and power system implications

For the purposes of understanding how changes in load may impact power system security over time, the following changes should be allowed for:

- **Substantial increases in electronic loads** – This especially relates to data communication and processing, and EV charging. While electronic loads can be programmed to achieve a wide range of power modes and response characteristics, this needs to be specifically designed for. This comes at a cost, and it cannot be assumed that desirable grid response characteristics will be inherent in electronic devices and equipment.
- **Substantial increases in constant power loads** – This is most apparent in the uptake of EVs and stationary batteries. If not effectively managed, these loads can exacerbate power quality issues in relation to nominal voltage and frequency. For example, a constant power mode device will maintain its power draw regardless of a drop in local voltage, rather than reducing its power consumption as would occur for constant current or constant resistance loads. Furthermore, in a constant power mode operation, a drop in voltage leads to rise in current consumed which can amplify the drop on voltage leading to voltage collapse. This phenomenon can reduce the inherent stability of power systems to voltage disturbances. The same principle can be applied for frequency disturbances.
- **Loads are becoming more flexible and price responsive** – This is especially true for thermal loads and EVs where electricity demand and the final energy-using application can be decoupled, allowing electricity demand to be shifted in time at a low cost. The primary risks associated with this is a loss of load diversity related to coincident demand peaks and troughs and high ramp rates, as well as their inherent vulnerability to loss of communication and cyber-attacks.

These trends each present both risk and opportunities for grid operation and these are explored further below in the context of EV charging. Outside of EV charging, datacentres present a significant area of load growth and represent some uncertainty in relation to their load sizes and grid performance characteristics. Overall, distribution networks are the ‘canary in the coal mine’ for these trends and are likely to experience localised impacts, associated with long-run changes in load characteristics, long before they are experienced at the transmission scale. An exception to this may be frequency disturbance ride-through performance, which also needs to be considered at a NEM-aggregate level.

Standards for loads have typically focused on local power quality, consumer experience, efficiency and safety over any potential interaction with the control of the electricity grid, resulting in a focus on power factor and reduced harmonics. Other standardisation efforts include the implementation of demand response schemes reliant on application layer standardisation and common information models (e.g., AS/NZS 4755) for distribution networks and emergency reserve market participation (e.g., RERT[18]).

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[18] AEMO (accessed 12 July 2023) *Reliability and Emergency Reserve Trader*

Potential standards-based approaches to manage risks associated with EV charging as discussed in Chapter 5 below.

Inductive (i.e., motors), resistive (e.g., bar heaters and filament bulbs), and capacitive (e.g., fluorescent lighting and capacitors) loads were relatively stable, known loads for the power system. SMPS have become a significant load with the transition to an interconnected world of electronic devices.

Individual electronic devices have little 'inertia' and no visibility to power system operators. These devices can also include a range of battery types (and sometimes a UPS) as well as DC power supplies using inverter/rectifier technologies. The inertia-like behaviour provided by synchronous electric motors is reducing as inverter and rectifier controls are introduced. This loss of inertia on the load-side is likely to grow over time.

These loads all have the potential to distort the power curve[19] and introduce harmonics into the system, increasing neutral currents and risks for distribution networks if first level protection systems fail. Loads coupled with storage (including heating/cooling loads and battery storage/EVs) will also increase 'cold load pickup' behaviour, with devices all requiring re-charging, and hence high-power demands, after a blackout. If not managed, this could put additional strain on system restart procedures.

If unaddressed at the distribution level, the aggregate of these changes across distribution networks may roll-up to a transmission system impact, bringing new issues to the power system. Power quality requirements and specifications can help, but other features such as smart control, and standards that promote ride-through behaviour may need to be considered by AEMO working in collaboration with DNSPs, who will experience many of these issues first.

Over the long term, changes in load dynamics represent a risk to system operators even without considering electrified transport. EV charging is, however, a case study in the changing nature of load which may contribute, or help mitigate, the risks discussed above. EV charging is the focus of the remainder of this report.

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[19] The relationship between the active power delivered to the electrical load and the voltage at the load terminals in an electric power system under a constant power factor.

3. POTENTIAL CONFIGURATIONS FOR EV CHARGERS

There are a range of EV charger designs that may create or exacerbate system security risks. EV charger configurations, on-board and off-board the vehicle, are outlined in the following section to support an assessment of potential risks that may occur from an EV and EVSE fleet of sufficient size.

The Electric Vehicle

The key functional elements of an EV with respect to charging are the on-board charger, the charger controller, and the battery (including the batter management system). These are complemented by communications and isolation systems, as described further below.

- **On-Board Charger** (OBC) – a system housed in an EV to convert power between mains AC to DC for battery charging (or discharging in a bidirectional case). OBCs vary by power capacity, cooling method, physical volume, mains phases supported, DC voltage range, uni/bidirectionality, grid synchronisation capability and other factors.
- **Charge Controller** (CC) – also known as the Electric Vehicle Charge Controller (EVCC), this component controls DC charging (and discharging for V2X) of an EV's battery pack. Some OBC designs incorporate the CC as a discrete device, reflecting the increasing need for dedicated computational resources.
- **Power-Line Communications** (PLC) – where the system conforms to ISO 15118, high-level communications are performed over PLC. This necessitates that both EV and EVSE have dedicated hardware able to communicate via PLC. Where this specialist hardware is required, it is included within the CC. The CC may also manage secure communications for ISO 15118, in which case it may incorporate additional components for encryption. Some high-level communications standards (e.g., CHAdeMO) use a different physical pin to carry EV-EVSE communication.
- **Battery Management System** (BMS) – a BMS monitors and controls the traction battery (the main battery) to assure safe operation and longevity of the energy storage system. It also detects any relevant fault conditions.
- **Isolation Monitoring** – implemented to determine critical fault states in a DC power system. Faults typically manifests as either a low resistance path between positive and negative terminals, or between either terminal and an EV or EVSE chassis. Detection of a fault state requires immediate isolation of the DC source to ensure safety.
- **DC relays** – used to isolate DC, either in the EVSE (in a DC EVSE) and/or in the EV.[20]

On-Board Chargers

The design of an on-board charger can be expanded further into power conversion and power quality systems complemented by system control and metrology functionality, as outlined below, and shown in Figure 7.

- **Input/Output Filtering** – input filtering typically exists in an OBC to reject noise which would otherwise propagate throughout the system. Electromagnetic interference may be conducted or radiated into the OBC from sources internal or external to an EV. Input filtering allows for greater optimisation in downstream stages of the OBC, and for higher quality DC to be delivered to the traction battery. Where an OBC is bidirectional, filters need to serve both as input or output filters and must target high-quality DC and AC output (particularly where grid synchronised).
- **Rectification and Power Factor Correction** (PFC) – this stage is concerned with conversion between AC and DC power and keeping the power factor[21] as high as possible to improve charging efficiency.

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[20] The terms 'relay' and 'contactor' are often used interchangeably.

[21] Maintaining the ratio of real power absorbed to apparent power moving through the system as high as possible: in short, maintaining conversion efficiency.

- **Galvanic Isolation** – isolation is used to prevent electrical shocks and system damage by physically isolating the DC circuit whilst allowing current to pass. Breakdown of any insulators (designed to operate within a particular voltage limit) is prevented, as is leakage to low-voltage circuits (which would result in system failure).
- **DC/DC Conversion** – rectified DC (at a voltage as a function of the mains) is manipulated to whatever DC voltage the traction battery (or EV high-voltage DC bus) requires.
  Various DC/DC topologies are typically implemented in unidirectional and bidirectional OBCs with design and integration considerations across galvanic isolation and DC/DC stages. The DC/DC conversion stage may often include the galvanic isolation.
- **System Control and Metrology** – as with EVSE, state monitoring and automation control are essential functions within an OBC, which may either interact with or include Charge Controller functionality. Similarly, an OBC must include a metrology solution on both AC and DC sides to ensure correct functionality. Where the OBC is bidirectional and performs AC V2G (i.e., grid synchronised output), the metrology solution needs to incorporate line frequency sensing to ensure correct synchronisation with the local mains supply. Metrology requirements in this case may extend beyond control and to billing, regulatory compliance, and services market participation.

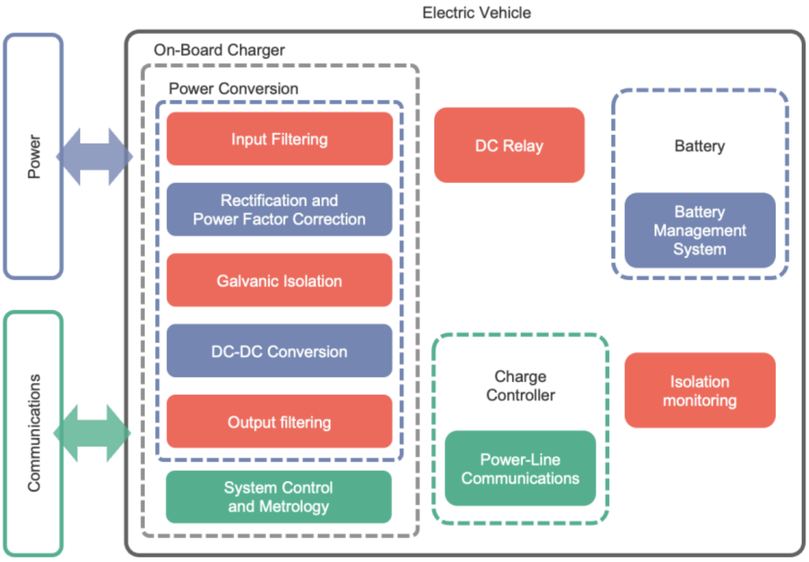

Figure 7 – Key elements of charging systems within an electric vehicle, including on-board charger for AC-DC power conversion. Power is shown in blue; communications is shown in green; protection systems are shown in red.

Design developments

Efficiencies in both unidirectional and bidirectional designs are rapidly improving with the recent commercialisation of wide-bandgap power semiconductors. These solutions, however, operate at higher switching frequency and necessitate faster control solutions within the OBC.

Bidirectional capability requires explicit software and/or hardware design. The functional requirements of AC V2G are being significantly revised given the rapid evolution grid connection and smart grid control requirements, and high-level communications. V2G OBC system control and metrology infrastructure objectives are also evolving.

However, technological advancements have/will reach a point where the bi-directional capabilities may largely be a software update rather than an upgrade to the hardware design. Devices which use active rectification (digital rectifiers) rather than a diode rectifier can be converted into a bi-directional charging system. Stakeholder have reported that by 2026-27, most of the EV/EVSE OEMs in the UK will be capable of bi-directional functionality even if they are not being sold as such.

AC EV Supply Equipment

EVSE can be broadly categorised into AC and DC configurations. AC EVSE are simpler to integrate with an AC power source as the power conversion is carried out by the OBC within the vehicle. This equipment is focused on passing AC through the vehicle with the addition of control and protection systems. The relevant functional elements are explained in more detail below and shown in Figure 8.

- **AC Protection** – relays (one per phase) are used to isolate downstream current pending operational state (e.g., proceed with charging) or a fault condition.
- **AC Metering** – measures voltages, current and frequency associated with a given part of the power system. Such measurements can be used for charging system control, billing, regulatory or market compliance or (in bidirectional charging) for grid synchronisation.
- **Automation Layer Controller** - Manages the operation of the EVSE as a machine given all relevant system states and application requirements e.g., if State Monitoring observes whether an AC protection element is open or closed, Automation Layer Control commands it towards either state as necessary.
- **State Monitoring** – constantly checks the state of critical systems within the EVSE, providing information that is used to determine the safe, correct operation of the EVSE. States that are both within normal operation (e.g., door sensing) and critical (e.g., contactor weld detection) are observed in this functional block.
- **Leakage Current Detection** – determines whether leakage currents (currents flowing from equipment to chassis or ground) are present. Leakage currents are fault conditions and require charging to be terminated immediately. Market requirements for leakage detection are evolving towards greater stringency and consumer protection (e.g., EU and NZ markets requiring Type B RCD protection or RDC-DD within the EVSE)[22].
- **Signalling and Communications Interface** – available charging capacity and readiness for charging are communicated between EVSE to the EV through the control pilot pin on the charge connector. Where high-level communications are supported by both EV and EVSE, these communications are managed through a dedicated functional element.
- **Application Layer Controller** – manages application layer functionality, allowing consumers and external agents to interact with the EVSE. This may be locally, via displays and buttons, or remotely using communications protocols.
- **EVSE Router** – manages bidirectional communications through the EVSE to a local or wide-area network as required.

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[22] AS/NZS 3000

- **Human Machine Interface** (HMI) - Provides physical engagement with users, which may include a display, status LEDs, a web interface, user identification hardware (e.g., an RFID reader), a payment terminal and the like, as required.

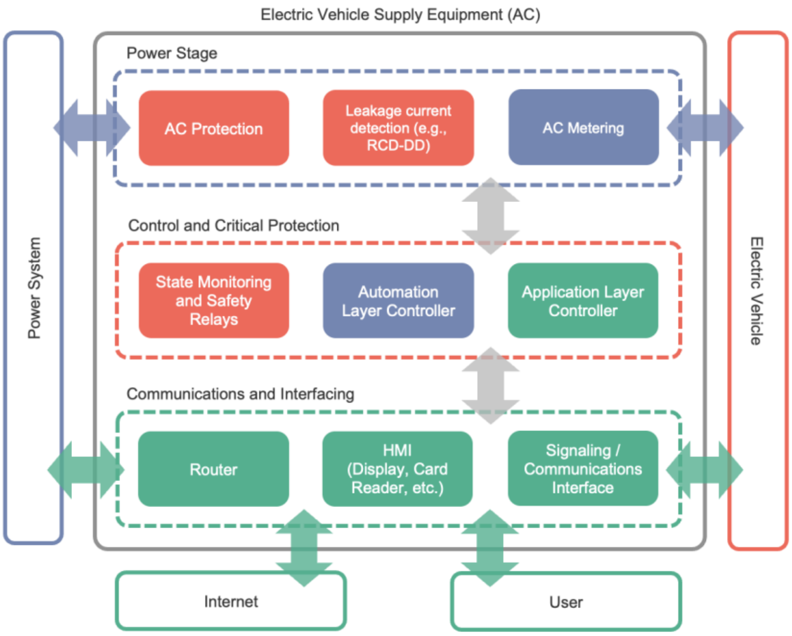

Figure 8 – Key elements of electric vehicle supply equipment for AC charging, where power conversion ultimately occurs in the vehicle. Power is shown in blue; communications is shown in green; protection systems are shown in red.

The Application Layer

The application controller may incorporate additional components and functionality to facilitate secure communications including encryption. The EV-EVSE communications standard, ISO 15118-2, mandates cryptographic random number generation and that the EVSE authenticates with the EV using Transport Layer Security (TLS). The later revision, ISO 15118-20, makes TLS authentication mutual and introduces stronger cyber security provisions. As a result, ISO 15118-20 is not backwards compatible with ISO 15118-2. It is, however, possible for an EVSE (or EV) to support both (and preceding standards), and to negotiate communications at the highest standards mutually supported.

DC EV Supply Equipment

DC EVSE require AC to DC power conversion equipment to be added to EVSE functionality, as well as additional safety and protection systems. Much of this is like that explained above for on-board equipment, with the addition of temperature sensing at the connector coupling and protection on both AC and DC stages, inclusive of isolation monitoring. This is especially important in some high-power charging implementations where active cooling is used to maintain safe operation.[23]

- **Temperature Sensing** – temperature sensing in the connector allows temperature rise with higher currents to be monitored and controlled within thermal limits by managing charging power throughout the session. This is a requirement of some DC charging implementations.
- **Auxiliary Power Supply** – whilst mains AC is rectified for battery charging, many other functional units in an EVSE require much lower (often DC) voltages. This is provided by an auxiliary power supply.

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[23] These active systems may include liquid cooling, which can produce a better customer experience through smaller, lighter cables. It does, however, add complexity.

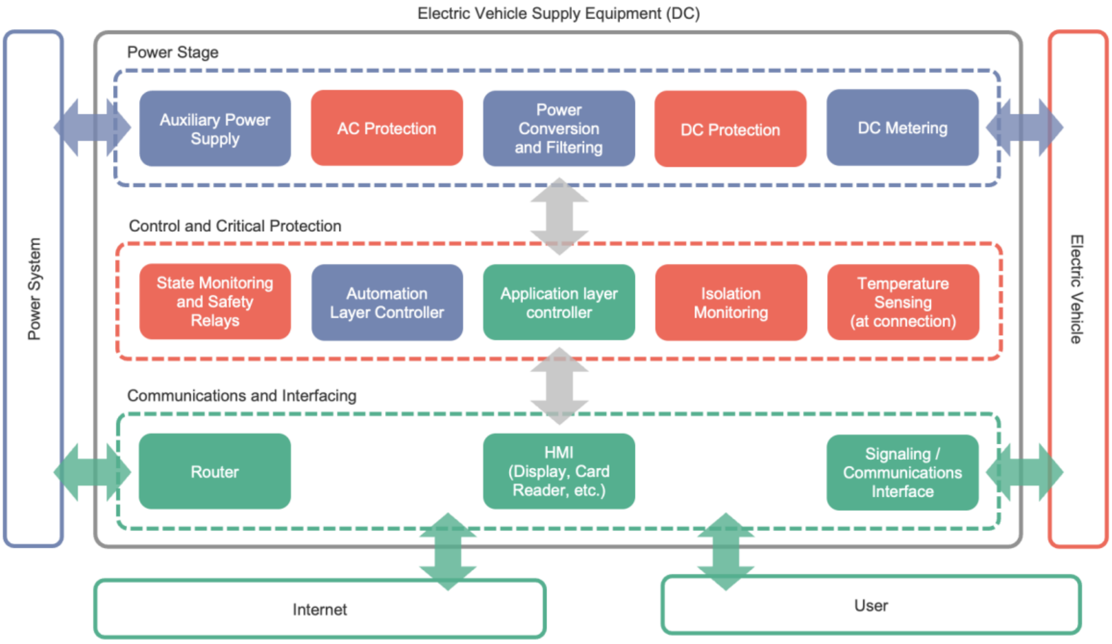

Figure 9 – Key elements electric vehicle supply equipment for DC charging, including added protection systems for high power flows which requires thermal monitoring.

4. INTERNATIONAL REVIEW

International power systems

United Kingdom

Sygensys delivered a report for the National Grid ESO in the UK on the impact of EV charging on short term frequency and voltage stability, and cascade fault prevention and recovery.[24] The report outlines six ways that EV chargers present a risk to power system security:

1. **Step**: too many chargers switching on/off simultaneously
2. **Ramp**: too many chargers switching on/off in minutes
3. **Oscillations**: many chargers switching on/off repeatedly
4. **Degraded stability**: increased risk of post-fault collapse
5. **Demand control**: erosion of conventional defences
6. **Restoration**: erratic behaviour after system restart

The analysis suggests that faults observed in PV systems might also be seen in EV/EVSE systems as the inverter algorithms have common design elements. Examples of such incidents referred in the Sygensys study include:

- Mass disconnection leading to widespread tripping from a line-to-ground fault in Texas interconnection in May 2021
- The need for frequency services after a delayed reconnection of PV after a fault experienced at a PV plant in Southern California
- The loss of generation after an over frequency response from DPV in Germany
- Voltages rise, Sub-Synchronous Torsional Interaction (SSTI) and Fault Induced Delayed Voltage Recovery (FIDVR) in California

Other issues discussed in the Sygensys report include:

- Loss of load from EV charging leading to an over-voltage/over frequency cascade event
- Lack of load relief capabilities by EVSE, which impacts stability of transmission and distribution due to voltage sag and frequency stability, and then leads to an increased risk of system oscillation (including Sub-Synchronous Oscillation, SSO)
- EV charging reconnecting before embedded generation, impeding system recovery.

Sygensys found that while smart charging can shift demand out of peak periods, if communication is lost, smart charging can default to behaviour that may increase coincident loads. At the extreme, a sudden loss of load diversity has the potential to physically damage power system infrastructure and trigger Low Frequency Demand Disconnection (LFDD) which is the UK equivalent to Under Frequency Load Shedding (UFLS).

The research suggests that while grid-forming inverter technology applied to V2G EVSE may help address falling inertia, it could increase the possibility of stable islands forming. It was also noted that capabilities for reactive power control could be incorporate into EV chargers, and dispatchable V2G could provide frequency balancing services.

The UK has adopted Engineering Recommendation ENA G99 to provide technical requirements for EV/EVSE with V2G capabilities to connect to distribution networks[25]. The *Electric Vehicles (Smart Charge Points) Regulations 2021* were also introduced in UK to address poor implementation or failure of smart EV

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[24] Sygensys (2022) *Resilient Electrical Vehicle Charging – Work Package 1*

[25] Energy Network Association (2021) *Engineering Recommendation G99 Issue 1*.

control systems which could lead to excessive ramp rates that would destabilise the grid[26]. These regulations include.

- Smart functionality – charge point must be capable of communicating and responding to electricity flows and provide services such as DSR.
- Retain smart charging functionality regardless of electricity supplier.
- Retain charging to EV in the event of loss of access to communications network.
- Intercept the user from overriding default settings in EVSE such as DSR or randomised delays.
- And other control settings for measurements, control systems (off-peak charging setting), Security and Assurance.

North America

A report from the North American Electric Reliability Corporation (NERC)[27] highlights the need for EVSE OEMs and electric utilities collaboration to develop strategies for ensuring reliability and security of bulk power system.

The NERC has facilitated discussions on impacts of EV charging on grid reliability covering EV charger interconnection standards and the impact of EV charging on North American demand forecasts, distribution systems, and bulk power system reliability. They report the following findings:

- Using a constant current control strategy rather than a constant power control strategy during normal operations is recommended as ‘grid-friendly’.
- Power factor should be maintained at 0.985 or higher for AC supply voltages between 80% to 110% of nominal voltage, to ensure that distribution networks do not experience significant reactive power draws and negative impacts on voltage stability across the transmission-distribution interface.[28]
- Research found that, to support grid frequency response, EVSE must be programmed with the capability to reduce current draw during severe frequency excursions (less than 59.7 Hz) before UFLS levels are reached, and ensure response occurs within 100-200 ms. This relates to a programmable current consumption droop characteristic, with an adjustable range and a default value of 5%.
- Dynamic response from EVSE (measuring and responding to terminal voltage and current by managing EVSE power consumption) were considered essential for ride-through performance, and details are to be investigated through further modelling and validation efforts.
- Response time for voltage ride through is recommended to be less than 20 ms.
- Measurements must be rapid and communicate quickly for the power electronics in EVSE to be dynamic and attend to real time conditions.

In summary, North American utilities’ primary focus is to understand behaviour of EV/EVSE during normal operation and during grid disturbances originating from the transmission network.

The NERC study explored various strategies to enable EVs to behave in a grid friendly manner (EV/EVSE supporting restoration and stable operation) during and following disturbances and highlights other critical aspects such as cybersecurity. The study recommends collaboration of EV/EVSE OEMs, national labs and NERC (cross-sector stakeholder engagement), standardising the form of information exchange and modelling of EVSE performance as next steps to understand impacts of EVs on the network.

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[26] Office for Product Safety & Standards (2021) *Complying with the Electric Vehicles (Smart Charge Points) Regulation 2021*

[27] NERC (2023) *Electric Vehicle Dynamic Charging Performance Characteristics during Bulk Power System Disturbances*

[28] AS/NZS 4777.2 requires a capacitive power factor at voltages below 220V/0.95PU.

Norway

The adoption of EVs in Norway is the one of the highest in the world. Around 54% of all new cars sold in 2020 are electric and more than 12% of parking lots have EVSEs[29].

The *Norway Public Study*, released in June 2022, revealed several categories of current power system challenges.[30]

1. Rapid increase in load and distributed generation connection inquires.
2. Prolonged lead times in connection process.
3. Challenges with handling large and uncertain electrical loads related to power trading between regions, load forecasting, policy changes and electrification.

This study also identified localised capacity issues in transmission and distribution networks pose a barrier to increased EV load growth. To mitigate the cost of inefficient network upgrades associated with growing demand, the study recommended:

- Changes to grid operational policies
- An emphasis on collaboration between network companies, to exchange information and data
- Energy efficiency measures to reduce peak demand
- Increased utilisation of demand-side flexibility
- The use of distributed generation combined with energy storage
- DSOs (Distribution System Operators) assess their own network challenges and identify those that can be addressed through demand-side flexibility.

Current regulations require power system assessments (PSAs) to include an evaluation of demand flexibility and development of alternative balancing resources within the study area and several demand-side flexibility pilot programs and initiatives have been undertaken:

1. NorFlex, including project Demo Glitre, which explored flexibility from EVSEs in car parks.
2. Enova established research to identify potential regulatory reforms to promote demand side flexibility.
3. The Norwegian Water Resources and Energy Directorate (NVE) is developing a governance model for the industry for digital collaboration (interoperability and data sharing).
4. Power System Investigations (KSU), a foundation in NVE's, to enable network companies to plan and coordinate network in a long term.

Norway's primary focus is on mitigating the need to upgrade their existing transmission and distribution network to keep pace with growing EV loads. Various demand-management pilot programs, interoperability standards initiatives and network upgrades are underway, which sit alongside efforts to optimise power flows between neighbouring national transmission networks.

The Netherlands

The Dutch transmission network (operated by Tennet) has significant spare capacity such that only 20-30% of maximum transmission capacity is typically loaded. A 2022 Energy Law planned to support greater use of demand-side responses and other measures to create more flexible and efficient energy systems and markets.

Netherlands ranked first in 2019, for highest charging infrastructure concentration globally and ranks second in Europe (behind Norway) for EV uptake.

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[29] Government of Norway (2023) *Norway is electric*

[30] Government of Norway (2022) *NOU 2022:6 about the development of the power grid*

DSOs in Netherlands have identified smart charging as a key measure to mitigate EV impacts on the grid and some of the DSOs equipping public charging equipment with smart charging capabilities. This initiative was complemented by a €5 million grant to install V2G chargers.

Other notable initiatives include:

- **ElaadNL** – a partnership consisting of Dutch grid operators, founded as a knowledge-sharing and collaborative innovation centre for smart charging and related knowledge domains. Elaad provides test facilities allowing EVs, EVSEs and related systems to be evaluated. ElaadNL also hosts the Open Charge Alliance, which created (and maintains) both the Open Charge Point Protocol (OCPP) the Open Smart Charging Protocol (OSCP).
- **City Zen Project, Amsterdam** – an ongoing project in Amsterdam area, that tests V2G technology to support DSO grid stability objectives.

Despite very high EV uptake, the strength of Dutch electricity networks has meant no significant problems have been encountered with EV integration to date. To support ongoing infrastructure roll-out, however, the Netherlands has assumed a global leadership position on interoperable EVSE management including support for the development of energy management and bidirectional charging functionality in OCCP.

These initiatives have been developed by distribution network operators to help manage localised potential capacity constraints and enhance broader EV driver experience outcomes.

China

China ranked second in electric car sales market share at 16% in 2021 and represents the world's largest EV market.[31] Although, limited information is publicly available at present about specific issues with EV integration, China is making massive investments into expanding their existing network capacity, with EVs likely being a significant contributor to overall load growth.

Several initiatives are underway to explore V2G and Smart Charging, as an alternative to upgrading transmission and distribution networks. A 2021 report by International Council on Clean Transportation[32] has recommended collaboration between government, research, and business to:

1. Utilise renewable energy to support growing EV demand, and
2. Encourage V2G programs to help manage peak loads.

These recommendations have also been reflected in China's *New Energy Vehicle Industry Development Plan (2021-2035),* which also encourages local government to promote V2G and demonstrate new power dispatch and control capabilities[33].

China is progressing major transmission and distribution network upgrades as part of its 'Unified National Electricity Market' objective[34]. EV charging is one class of load growth that is being planned for however it is not specifically referenced or publicly reported on. This strategy includes a focus in linking major load and generation centres and the incorporation of variable renewable energy and traditional generation resources.

EV-specific strategies are largely limited to facilitating collaboration between utilities, research institutes and businesses and pilot programs focussed on local renewable energy integration and V2G to mitigate load growth. There is limited publicly available information on the status of these initiatives or research outcomes from pilots. Further data may become available over time.

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[31] IEA (2021) Electric *Car registrations and sales share in China, United States, Europe and other regions, 2016-2019.*

[32] ICCT Policy Update (2021) *China's New Energy Vehicle Industrial Development Plan for 2021-2035*

[33] NDRC (2020) *New energy vehicle industry development plan (2021-2035)*

[34] NDRC (2021) *Action Plan for Carbon Dioxide Peaking Before 2030*

Japan

The Central Research Institute of Electrical Power Industry (CRIEPI) performed a study in June 2022, focusing on control of EV charging[35]. The report highlighted that numerous countries are ahead of Japan in EV adoption and refers to European countries as a guide to facilitate development of EV charging infrastructure and to promote effective grid integration.

The CRIEPI report recommends that following strategies:

- Establish control strategies for EV charging to address localised capacity issues. This includes control of EV charging capacity and timing based on location.
- Focus on EV demand at commercial facilities and studying the impact on distribution grids
- Study the augmentation required on LV network to support EVSE installations.

Further research[36], focused on the relationship between peak load coincidence and regional mesh size, studied 40,000 EVs in the Aichi prefecture, with three different mesh area sizes, (1km, 5km and 10km). Findings suggest that in a high fast charging scenario, the peak load in 1km mesh can be highly coincident, compared to the larger mesh areas where the peak loads were smoother. The study also identified a direct negative relationship between rate of load increase (ramp rate) and mesh size. Recommendations were made to ensure attention was given to local distribution capacity as well as potential demand peaks at the transmission scale.

TEPCO, the grid operator of Japan, has undertaken a trial of V2G, using electric vehicles as virtual power plant resources, in a business fleet charging context[37]. One of the goals of this program is to use EVs to improve power system stability. The program is seeking to assess and address bidirectional load changes on networks however, trial outcomes have not been located.

Japan has a relatively low penetrations of BEVs but has significant concerns in relation to broader energy security matters that permanent its energy innovation ecosystem. This is reflected in trials and studies focus on EV smart charging and V2G to address localised grid constraints and resource adequacy issues.

South Korea

South Korea, like Japan, is also focussed on trials and research to develop an understanding of the impacts of EV charging on power system security, and numerous governments led initiatives have been established in partnership with the network operator Korean Electric Power Corporation (KEPCO), a state-owned enterprise.

The 2021 KEPCO Annual Report[38] noted that the Korea Electric Power Research Institute (KEPRI) is engaged in research into distribution system planning, operation, and management. The research also covers,

- Using EVs as for demand response and to support stable power system for stable operation.
- V2G and smart charging

As of 2022, unidirectional charging has been a major focus and AC V2G is being deployed with 7kW charging and 5kW discharging under a partnership between with Hyundai, and Ulvac.

Other programs and studies involving KEPCO include:

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[35] CRIEPI(2022) *UK system Design and Distribution Operator's efforts to develop EV charging infrastructure considering efficient equipment formation focusing on controlling charging time and location*.

[36] CRIEPI (2023) *Effect of High Output of EV Quick Chargers on Peak Load on Power Systems – Relationship between Regional Mesh size and Smoothing effect if Charging Demand*

[37] Tokyo Electric Power Company Holdings (2020), *Trial Operation of V2G Business Development Project utilizing Electric Vehicles as Virtual Power Plants*

[38] KEPRI (2021) *Research Activity Report 2021*

- EV charging load management system for power distribution networks focussing on monitoring load and controls for power system operation[39]. Some of the functions explored included.
    - Providing real time information for monitoring EV charging status,
    - Standard interfaces for communications,
    - Distribution system load analysis as an input into network planning and operation.
- Developing service provider systems to support participation in demand response service arrangements, incorporating V2G.
- Government funded research to study communication and control technology for AC and DC bidirectional power transfer.[40]

The primary focus in South Korea is on the development of systems to support smart and bidirectional charging to address potential distribution network constraints and resource adequacy concerns. This is being progressed in the context of vertically integrated, state-owned arrangements for electricity supply which allows government funding for trials and research to be aligned with distribution network planning. No initiatives have been identified that address identified concerns in relation to transmission-scale power system security.

Academic research

Overvoltage due to synchronous tripping of EV chargers

Kundu and Hiskens (2014), at the University of Michigan, have explored the nature of voltage rise phenomena due to sudden load loss.[41] This research studied two distribution test networks:

- A 23kV, 10 node transmission (primary) feeder
- A 24.9kV, 34 node distribution feeder

The study found that, under simulated conditions, voltage sag events on a network with large group of EVs, can lead to simultaneous disconnection of EV chargers, and a corresponding overvoltage effect.

Overall, the modelling results showed that tripping 33% of EV charge loads at every node resulted in a voltage rise on the feeder above their voltage bounds.

Results from the 23kV test feeder analysis also showed that:

- The study tested the minimum share of EV load required to produce an unacceptable post-disturbance over voltage effect. At 100% loading, overvoltage occurred when EV load reaches 21% of total load. When the network was overloaded (135%) overvoltage occurred when EVs were only 9.6% of the total load.
- The vulnerability of the network is highest when the EV load is connected at the remote end of the feeder. A 20% increase in the share of EV loads at a node closest to the substation has the same effect as 6% increase in EV load at furthest node.
- The effect of voltage sags tends to be a function of distance from the substation. For a 300 ms voltage sag, the number of EVs connected at each node fell from 200 to 165 (~18%) at the closest node to the substation. At the furthest node, EV connections fell from 85 to approx. 35 (~59%).

The second network area tested was a 24.9 kV 34 node standard feeder. Results show that:

- For feeder loading at 100%, less than 20% of EVs tripping is enough for node post disturbance voltage to reach 1.1 pu.
- Testing at two different nodes, with 70% and 80% EV share of load, created almost the same likelihood of post disturbance rise in voltage.

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[39] KEPCO KDN (2023) *Energy New Business, Electric Car*

[40] KERI (2023) *Power Grid Research Division*

[41] Kundu and Hiskens (2014) *Over Voltages due to Synchronous Tripping of Plug-in Electric-Vehicle Chargers Following Voltage Dips*.

- EVs furthest from substation contribute most to post disturbance overvoltage.
- For 100% EV share of load, a load drop of 20% results in voltage rise of 1.1 pu. For a similar load drop, the 3-phase model results indicated that, when an imbalance across the three phase exists, a 17% load drop could lead to overvoltage issues and significant imbalance issues.

The ‘AC service limit’ setting assumed for the EVSE equipment that was modelled, is consistent with the SAE J2894. Changing the standard to address the tripping of EV chargers is therefore one way to mitigate overvoltage disturbance effects.

This research provides insight into how AC service limit settings contribute to EV load disconnection (and corresponding overvoltage effects) in response to short-duration voltage sags. This paper concludes that, when sufficiently large groups of EV disconnect as a response to voltage disturbances on the network, this could lead to high voltages (beyond 1.1 PU) on a distribution network.

Achieving Controllability of Electric Loads

Network management arrangements are an important consideration for EV charging and the other large loads. In general, they must maintain customer expectations for reliability while delivering a reliable resource to the power system.

Callaway and Hiskens (2011) explored control arrangements to support grid operations.[42] They argue that load management arrangements can aim to be:

- Fully responsive – enabling high-resolution system-level control across multiple time scales.
- Non-disruptive - having a minimal effect on end-use performance such as EV battery state of charge (SoC). Non-disruptiveness underpins the cost and sustainability of the load control service.

The paper demonstrates two control strategies for managing EV demand:

1. Time-based load control strategy – curtailing or increasing PEV demand at certain times in a 24hr period.
2. Price based load control (demand management) strategy – User self-curtailment based on dynamic price signals.

In simulations of 4 million EV loads, a time-based strategy mitigated the decrease in demand during evening peak, however it resulted in the emergence of peaks at other times. The report recommended staggered start times for customers to reduce the intensity of the peak as has been subsequently applied in the UK with ‘randomised delay’ requirements under the Electric Vehicles (Smart Charge Points) Regulations 2021.

Price-based demand management strategies face challenges in achieving an adequate level of control and are more subject to the uncertainties in customer behaviour. It was also observed that as EV demand rises beyond certain thresholds, it can increase overall market prices, resulting in desisted charging. This can lead to oscillations across trading intervals.

Simulating an example of load controllability using control systems for 20,000 EVs, revealed that the temporal constraints that drive control decisions are directly related to customer willingness to participate and enrolment rates must be a key consideration in load control strategy design.

This analysis was based on an assumption of loads being unscheduled and not visible to central dispatch. Price-based demand management strategies using self-forecasting to system operators, or scheduling (e.g., utilising the Small Resource Aggregator market registration category and/or Schedules Lite), is an important area for future analysis.

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[42] Callaway and Hiskens (2011) *Achieving Controllability of Electric Loads*

Key insights from the international literature review

The international review explored current EV power system integration strategies in the US, Norway, the Netherlands, the UK, Japan, China and South Korea.

Norway and China, global leaders in EV uptake, have focused their priorities on upgrading their transmission and distribution network to meet increasing demand. Both countries have a strong focus on transmission interconnection of regional/national grids. Both countries are exploring demand management (including supporting V2G) to mitigate network expansion costs, as are each of the countries we have considered.

Otherwise, most of the international grids considered remain focussed on localised distribution network congestion and ramping issues. Studies in the Japan and other regions indicated a broad expectation that distribution network voltage management is the primary current concern. These issues become more diffuse at the transmission scale as load diversity increases.

The Netherlands has one of the most extensive networks of charging infrastructure in the world and is leading global efforts to standardise interoperability frameworks to achieve both demand management and consumer experience outcomes.

Both the UK and the US have commenced processes to consider the transmission-scale system security risks associated with high EV penetration (as opposed to resource adequacy and local network congestion issues). Relevant system security risks are well defined in the Sygensys study (UK) and the NERC study (US) as well as the academic research papers summarised above. These are further considered in the NEM risk assessment set out in the remaining chapters of this report.

Table 2: Summary of International Review

Countries	**Issues identified**	**Key focus areas**
United Kingdom	• EV charging response to disturbances causing disconnection of EV loads • Lack of load relief capabilities • EV charging impeding system recovery	• Smart charging and V2G technical requirements. • Communications and control settings of EV/EVSE
North America	• EV charging behaviour such as constant power mode operation • Response to frequency excursions.	• Understanding EV charging response to power system disturbances
Norway	• Handling large and uncertain loads, and lack of capacity of the existing network to accommodate EV uptake.	• Assessing transmission and distribution capacity adequacy • Smart charging and V2G
Netherlands	• No significant issues reported	• Initiatives to support collaboration of industry and network operators to trail V2G and smart charging.
China	• EVs are contributing to overall system load growth	• Investments in transmission and distribution capacity adequacy • Smart charging and V2G
Japan	• Localised capacity issues in distribution networks to accommodate EV uptake	• Control strategies for distribution-connected charging • Smart charging and V2G
South Korea	• Localised capacity issues in distribution networks to accommodate EV uptake	• Demand response and grid support capabilities of EV charging • Smart charging and V2G

5. EV CHARGING STANDARDS

While communications and interoperability standards for EVs and EVSE were not intended to be a focus of the current study, communication and control frameworks have risen to prominence via our literature review and discussions with international experts on the relative priority of risks to the power system associated with higher EV uptake. Overseas markets are moving to stipulate requirements for the *control* of EVSEs (including by distribution network operators) and broader interoperability. This is a key focus for international standardisation efforts and is addressed in the remaining chapters.

The standards landscape for e-mobility

Grid performance, and broader electrical standards, are generally not specific to the EV charging ecosystem. An exception to this is power quality requirements which are set out in SAE J2894.[43]

Recommended Practice

SAE J2894, *Power Quality Requirements for Plug-In Electric Vehicle Chargers,* provides guidance on OBC design and other charging sources (e.g., DC EVSE) including power quality and line interactivity requirements. The recommended practice focuses primarily on the appliance, and so does not provide specific guidance for behaviours that may adversely impact power system security in aggregate.

Examples of recommended settings described in SAE J2894 include:

- Withstand of voltage sags of 80% for more than 3 seconds.
- EVSEs should momentarily stop charging for voltage swell of 125% of the nominal voltage for more than 3 seconds.
- EVSEs should lose function for voltage swells of 175% of the nominal voltage for min 8ms or ½ cycle.
- IEC 718, IEC 146-1-1, and IEC 61851 are identified as relevant standards for frequency variations, in SAEJ2894, and recommends +/-2% of the nominal frequency to align with recommendations in other standards.
- Restart should be delayed for a minimum of 2 minutes with a pseudo-randomised timer. However, in the case of manual intervention, the EVSE must restart immediately. This requirement does not apply for SAE J1772 Level 1 chargers.
- For “soft start”, the standard recommends the rate of linear load rise is no faster than 40 Amperes per sec (A/s). This helps prevents voltage sags resulting from rapid input current.
- Offline behaviour of Inverters should demonstrate, Staggered Restart Cold Load Pickup (CLP) behaviour, for Level 2 AC and DC off-board chargers for example, delayed restart after loss of AC power to EVSEEVSE, voltage sag.

The settings that are recommended in SAE J2894 will need to be considered in a more comprehensive standards initiative, including international collaboration to determine the suitability of specific settings for different grid contexts.

Unidirectional charging

There is little in the Australian standards landscape to regulate the behaviour of EVs as a power system load, whether individually or in aggregate.[44] The design of equipment electronics, and their resulting load characteristics, can therefore be assumed to be driven by equipment protection, efficiency and product functionality considerations.

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[43] SAE International (2019) *J2894/1_201901: Power Quality Requirements for Plug-In Electric Vehicle Chargers*

[44] At the time of writing, Queensland requires EVSEs of a certain power level to be operated at certain times and be placed under direct load control. The intent of this can be interpreted to be, at least in part, to increase predictability and controllability of demand to contribute to local demand management objectives.

Bidirectional charging

V2G capable charging systems classify as an embedded generating unit under Chapter 5A of the National Electricity Rules and they are subject to basic connection service and model standing offer arrangements as if they were a solar or battery installation.

While no specific national requirements have been developed for V2G, they must comply with all relevant national and jurisdictional regulations that apply to solar and stationary battery generating systems. This includes AS/NZ 4777.2:2020[45] irrespective of whether it is in the vehicle (AC V2G) or external to the vehicle (DC V2G).

At the time of connection to an electricity distribution network, network operators must ensure that V2G capable charging systems are compliant with AS/NZS 4777.2. This is typically by reference to the Clean Energy Council *Approved Inverter List*, though in some circumstances DNSPs may deem products to comply even when they are not listed. Local grid code compliance may be challenging for AC V2G as vehicle systems are generally intended for global markets.

Internationally a revision to ISO/IEC 15118-20 is intended to harmonise approaches to communicating grid codes settings to EVs, for the purposes of AC V2G. This is especially important in Europe where vehicles often travel between (and may wish to bidirectionally charge in) different network areas with different grid codes. In principle, the same issue could apply for a vehicle travelling between the mainland and Tasmania where AS4777.2:2020 requires different regional inverter settings must apply.

As a requirement of ‘connection’, AS4777.2:2020, does not address requirements for market participation. Metrology, and response requirements, are set out the Market Ancillary Service Specification (MASS)[46] for frequency response devices which can be applied unidirectional or bidirectional changing.

Australian inverter standards

AS4777.2:2020 is the appropriate place to establish grid performance standards for bidirectional chargers. The standard includes considerations for multiple-mode inverters, which apply to bidirectional charging. Relevant specifications captured within this standard include:

- Demand response modes and external disconnection requirements,
- Power quality response modes (e.g., volt response, fixed power factor mode, reactive power mode),
- Limits for sustained operation (e.g., RoCoF, voltage disturbance and phase angle shift withstand, sustained operating limits for frequency and voltage, relevant load shedding behaviours)
- More elemental protective functions (e.g., passive anti-islanding/voltage and frequency limits, active anti-islanding, automatic disconnection)
- Export and generation limits.

Australian standard 4777 provides detailed voltage disturbance performance requirements including definitions of trip times and restoration times under different conditions. For specified voltage disturbances, the inverter must quickly cease power generation and then restore power to pre-disturbance levels within a short time post-disturbance.

AS/NZS 4777.2:2020 requires that the inverter must remain in continuous operation for frequency excursions within ROCOF parameters. The standard also recommends active and passive methods for protection against anti-islanding.

AS/NZS 4777.2:2020 refers to various local and international standards. Local standards include AS 60038, *Standard voltages*, and AS/NZS 3000 *Electrical installations* and AS/NZS 61000 *Electromagnetic*

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[45] Standards Australia (2020) *AS/NZ 4777.2:2020 Grid connection of energy systems via inverters, Part 2: Inverter requirements*

[46] AEMO (2021) *Market Ancillary Services Specification - v7.0 effective 1 Feb 2021*

compatibility (EMC). Relevant references to international standards include IEC 62196, *Plugs, socket-outlets, vehicle connectors and vehicle inlets — Conductive charging of electric vehicles* and IEC 61851, *Electric vehicle conductive charging system*.

IEC 61850 – 7 – 420: 2021 builds interoperable solutions focused on implementing interfaces between products. Although this standard does not directly refer to EV/EVSE equipment, it provides insights into the features and behaviour that electronic devices shall have to address power system level issues. This standard was adopted globally, including in Australia[47]. Part 7 of this standard discusses the basic communication structure for DERs and Distribution Automation systems (DA) with the power system.

It defines operational functions of DERs that specify, Voltage and Frequency Ride Through functions along with implementation examples in Europe.

Energy star Program Requirements for Electric Vehicle Supply Equipment Version 1.2[48] provides product specification of EVSEs for certain criteria. On mode requirements, no vehicle mode, idle mode, connected functionality are some examples. These requirements focus on Level 1 and level 2 AC chargers, and DC Charger as defined in SAE J1772.

Aside from the general function of the EVSEs such as Primary functions of charger to provide power, operational modes (idle, no vehicle/disconnection mode) etc. the key settings identified are the demand response capabilities of EVSEs.

Communications associated with the Connected Functionality requires EVSEs to allow customers to modify charging schedules (both remotely via apps or on the EVSE station) and override DR settings set by the load management entities.

Such requirements can lead to situation where customer overrides an optimal charging strategy set by the load management groups on a peak hour, which then can lead to risks of voltage and frequency disturbances and imbalance of demand and supply on the power system when significant number of EVSE are modified on the network.

Energy Star report requires that when settings are overridden, the load management entity gets an update of the change in charger settings. Similar events can also occur when there is loss of connection. A loss of connection is defined as an event where the DRMS does not respond to 5 consecutive communication attempts from EVSE or vice versa, or 10 mins without connection whichever occurs first.

During a loss of connection, the requirements state that if the connection is lost after setting the DR event on the EVSE, then the EVSE proceeds with the setting as planned and returns to default state after the event is completed. For loss of connection at the time of setting DR event on the charger, the EVSE defaults to normal operation.

South Australia Technical Regulator Guidelines[49] outlines the requirements for EV/EVSE with Demand Response (DR) capabilities. The regulation only focuses on Level 2 AC charging as specified in SAE J1772:2017 *Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler* and Mode 3 charging as defined in IEC 61851-1:2017 *Electric Vehicle Conductive Charging System – Part 1*. This regulation excludes, Level 3 DC fast charging, Mode 4 DC fast charging and On-Board Charge Controllers (OBCC).

For demand Response, the regulation states that the technical standards *Open Charge Point Protocol (OCPP) 1.6 V2* (or higher) or *ANSI/CTA-2045-B:2021 Modular Communications Interface for Energy Management* are complying for EVSEs (both V1G and Bi-directional). However, the technical regulator may find alternative standards or methods that he deems suitable for compliance.

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[47] Standard Australia (2021) *IEC 61850 - 7 - 420:2021*

[48] Energy Star (2023) *ENERGY STAR Version 1.2 EVSE Final Specification*

[49] Government of South Australia (2021) *Technical Regulator Guideline – Technical Supply Equipment (EVSE)*

The requirements include, delay capability, where the EVSE operates on a time-based strategy to avoid surge of demand on the local network, randomisation for start and stop DR commands from the remote operator, to avoid mass simultaneous changes of DR events provided by similar EVSEs on the network. The regulation identified power quality support from EVSEs with DR capabilities as optional features if they don't come into conflict with the mandatory DRMs, which are mostly focused on establishing communication and control of charging.

International developments

Modern DER and inverter standards (including EVSE) are generally evolving in the same direction – away from disconnection during power system disturbance and towards ride-through performance. Metrology and response requirements are evolving to match this performance intent.

This includes IEEE 1547-2008, *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*, and VDE-AR-N 4105:2018-11, *Generators connected to the low-voltage distribution network – Technical requirements for the connection to and parallel operation with low-voltage distribution networks*. This alignment is important as both German and North American market considerations feature strongly in the development and standardisation of high-level communications between EV and EVSE. This in turn affects standards and frameworks for upstream communication, including between the EVSE a CSMS, and will shape the management of grid performance settings.

The role of EV to EVSE communications

The original standards for AC conductive vehicle charging, including SAE J1772 in particular,[50] describe some fundamental aspects of how vehicles interact with the grid. Charging is (at least quasi-statically) *constant current* in nature – the EVSE advertises the available current it can deliver, and the EV initiates charging at a current level at anything from 6 Amps to that advertised by the EVSE. These elements of SAE J1772 were adopted in IEC 61851, and so form part of signalling used in more modern EVs in Australia which adopt European connectors (Type 2 or CCS2).

Constant-current loads allow power to drop slightly as voltages sag and are thus considered 'grid-friendly'. In contrast to this, high-level communications (standardised internationally by ISO 15118) specify charging limits in terms of power, not current. This effectively leaves the OBC to determine whether charging is constant current (and thus "grid friendly") or constant power (not 'grid-friendly') as it tends to draw more current during voltage sag events, which may exacerbate power system instability.

It must be noted, however, that high-level communications support a range of options in managing charging events, including the setting of alternative power modes and active and reactive power targets.

Another benefit of high-level communications is the change in minimum load (from J1772's 6 Amp minimum) to very low (almost dormant) levels. As a charging session can only be initiated on the vehicle side, if an EV can be maintained at a very low rate of charge and raised rapidly as needed, then it is possible for EV to respond more rapidly to locally detected changes in the network state. In this case, the EVSE would detect the issues and communicate it to the EV to determine a response within the agreed parameters of the charging session.

In DC charging, power is primarily determined by a variety of limits (e.g., electrochemical, thermal, etc.) which vary throughout the charging event. Whilst DC charging is typically associated with relatively high-power levels, some are lower power levels comparable to typical AC (i.e., <22 kW) and may behave in a constant power manner.

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[50] This is technically a 'de facto standard', as it was not formally adopted, but was common to early PHEV and EV models sold in Australia.

The influence of smart grid standards

Smart grid standards are a core ‘standards set’ for determining the correct operation of EVs flexible resources (in addition to those for EV-to-EVSE and EVSE-to-CSMS communication). Internationally, smart grid standards include:

- **OCPP** – for Communication between the EVSE and a CSMS. OCPP is not currently a requirement in Australia although SA will require OCPP 1.6 V2 or higher by 1 July 2024.[51] Version 1.6 is superseded by Version 2.x (2.1 is required for standardised V2G interoperability). Version 2.x will not be backwards-compatible with 1.6.
- **IEEE 2030.5** – Australia is adopting CSIP-Aus (based on IEEE 2030.5) as the national profile for communicating dynamic operating envelopes from distribution network businesses to customer premises. These will typically be received by a site gateway device/inverter with local communication to the EVSE via OCPP or Modbus. The possibility of using IEEE2030.5 to standardise direct automaker-EV communication has also been canvassed in the US.
- **OpenADR** – The OpenADR 2.0b Profile Specification was approved as IEC 62746-10-1 in 2019 as a systems interface between customer energy management system and the power management system. OpenADR originated in Europe and is not currently used in Australia.
- **AS/NZS 4755** – is an Australian standards suite, published in 2017, defines instructions and minimum level of demand response functionality, and Demand Response Enabling Devices (DRED) that can be used to remote control electrical products. South Australia has proposed that, from 2026, EVSEs with demand control capabilities must comply with 4755 DRMs standards 4755.3.4 or 4755.2 (when published)[52].

Whilst various control topologies exist (e.g., smart grid controls communicated to the EV, EVSE, CMS, or an EMS as a client) none yet dominate any particular market. Smart grid standards could, however, allow utilities to communicate various limits and profiles in ways that are configurable, flexible, and resilient to loss-of-communications events.

EVSEs sold in the UK since Q3 2022 (for private, work and home, installations) must conform to the *Electric Vehicles Smart Charge Point Regulations 2021*, which require:

- Internet connectivity
- Prioritisation of off-peak charging
- Introduction of a randomised delay (default up to 10 minutes)
- Steps to promote consumer enrolment in managed demand response schemes, and
- Cyber security and anti-tamper features.[53]

This regulation applies to unidirectional and bidirectional charging equipment and is intended to influence (among other behaviours) ramping of aggregate EV charging loads in a system-wide context.

Whilst the specific mechanisms and standards by which this functionality is implemented are not mandated, the UK does have complementary initiatives describing technical requirements to implement such functionality in a smart grid context. These initiatives in the UK included the development of standards and codes of practice to support EV participation in demand response markets:

- **PAS 1878** specifies requirements and criteria that an electrical appliance needs to meet in order to perform and be classified as an energy smart appliance[54], and

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[51] SA OTR (2022) *Technical Regulator Guideline Technical Standard for Installation of EVSE*
[52] SA Energy mining (2021) South Australian Demand Response Performance Requirements
[53] UK (2021) *The Electric Vehicles (Smart Charge Points) Regulations*
[54] BIS (2021a) *PAS 1878*

- **PAS 1879** sets out a common definition of demand side response (DSR) services for actors operating within the consumer energy supply chain and provides recommendations to support the operation of energy smart appliances[55]

Evaluation of the PAS is underway to assess the benefits and challenges of the standard as currently drafted.[56] Updates to both of the PAS are planned ahead of commercial implementation within the GB market. Extensive efforts are also being made to, where possible, ensure alignment with International Standards to help drive economics of scale for OEMs manufacturing products for global markets.[57]

The current version of these regulations describes requirements quite specific to UK demand response market design. They do not account for Australian smart grid conditions, such as the emerging need for assets to be orchestrated by a site level operating envelopment. Currently it is not clear if the planned update to the PAS will address this issue.

A systems approach is required

The IEC Systems Committee for Smart Energy is currently developing the Systems Reference Deliverable IEC 63460,[58] *Architecture and use-cases for EVs to provide grid support functions*. Grid support functions are considered in defining functions for use-cases including frequency and voltage ride-through. In system architecture terms, it is envisioned that grid code requirement parameters, including ride-through, are passed through a CSMS to the EVSE. This is reflected in IEC 61850-7-420:2021,[59] *Communication networks and systems for power utility automation,* which include sections on voltage and frequency ride-through for the European and North American contexts.

North American standards organisations are taking a similarly strategic approach. ANSI Electric Vehicles Standards Panel (EVSP) recently produced a *Roadmap of Standards and Codes for Electric Vehicles at Scale,* which highlights concern about combined effects of EV chargers on the reliability of electricity networks.[60] A revision to SAE J2894/1 is noted to be in-development,[61] as are efforts to address an identified gap concerning ride-through requirements for V2G EVSE by IEEE and UL.[62]

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[55] BIS (2021b) *PAS 1879*

[56] GOV.UK (2023) Interoperable Demand Side Response Programme: successful projects

[57] BSI Group (2021) Energy Smart Appliances standards programme – PAS 1878 and PAS 8179 development stage

[58] IEC (2022) *Architecture and use-cases for EVs to provide grid support functions*

[59] IEC (2021) *Communication networks and systems for power utility automation*

[60] ANSI (2023) *Roadmap of Standards and Codes for Electric Vehicles at Scale*

[61] SAE (2020) *Power Quality Requirements for Plug-In Electric Vehicle Chargers* [WIP]

[62] Gap G9 outlines a recommendation to explore ride-through requirements for EVSE under 'grid service conditions' when EVSE are supplying power to the grid.

6. POTENTIAL COMPLIANCE FRAMEWORKS

AEMO’s ability to set standards for grid-connected plant

AEMO is responsible, under the National Electricity Rules for maintaining power system security and ensuring that the power system is operated within its technical limits, and achieving and maintaining a ‘secure operating state’ (Clauses 4.3.1(f) and 4.2.5).

In determining and applying these technical limits, clause 4.2.5 requires AEMO to take into account the capabilities of *all equipment involved in generating, utilising or transmitting electrical energy* (i.e., ‘plant’). While AEMO must take into account the capabilities of *all* plant, it has only been granted the express function of establishing performance standards applicable to plant as notified by Registered Participants (clause 4.14(n)) i.e., registered traders in energy and ancillary services markets. As a result, AEMO’s focus has traditionally been limited to large-scale generators (i.e., ‘Generator Performance Standards’).

AEMO has the ability to delegate to a ‘System Operator’, rights, function and obligations as it considers appropriate to achieve and maintain system security (clause 4.3.3(a)).

Compliance with generator performance standards is overseen by AEMO and Transmission Network Service Providers (TNSPs) through connection and registration processes. A Registered Participant who engages in the activity of planning, owning, controlling or operating a plant to which a performance standard applies must institute and maintain a compliance program (clause 4.15(b)).

Generators also have an obligation to follow AEMO dispatch instructions (clause 2.2.6(g)(4)) and these must be made by AEMO with reference to a specific generating unit (clause 4.9.5(a)(1)), i.e. units specifically notified by a Registered Participant.

The AER is formally responsible for monitoring Registered Participant compliance with the rules, including subordinate requirements such as technical performance standards and dispatch instructions (NEL clause 15(1) and Rule 8.7). The NEL provides for both civil and criminal penalties that can be applied to Registered Participants who engage in serious breaches by Application to the Federal Court of Australia. The AER maintains a public record of enforcement actions.[63]

Application to EV and other electronic loads

EV chargers (and other electronic loads being considered in this report) can be considered ‘behind-the-meter’ (BTM) resources in that they are not typically notified by Registered Participants and are therefore not visible to AEMO, or able to be subjected to performance standards or dispatch instructions.

Exceptions to this occur in relation to aggregations of small devices participating in frequency response markets. In this case, AEMO’s Market Ancillary Services Specification (MASS) sets a range of requirements relevant to the performance of the relevant market service. However, the tiny proportion of relevant loads that can be expected to be subjected to MASS requirements makes this an edge-case consideration.

AEMO may also impose technical requirements on scheduled loads and wholesale demand response units that are notified by a market participant. Other than bidirectional units, which are also registered as a generator (e.g., batteries), enX is not aware of any electronic loads (including EV chargers) being notified to AEMO in any market.

Integrating energy storage rule change

Several current reforms are aiming at promoting more direct participation of aggregations of small-scale assets in energy and ancillary services markets. These include the creation of the *Small Resource Aggregator* (SRA) category of market participant (as an extension of the Small Generation Aggregator

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[63] More information is available at: *Enforcement | Australian Energy Regulator*

Category) that could evolve to support the participation of EV chargers (uni and bidirectional) in energy and FCAS markets.[64]

An SRA is an Integrated Resource Provider who has classified a *small resource connection point* as one of its market connection points. Supply at the connection point must be limited to use by a *small bidirectional unit* connected at the connection point, or auxiliary loads associated with a *small bidirectional unit* or *small generating unit*.[65] AEMO is currently considering its position on the treatment of bidirectional EV chargers under SRA requirements. AEMO does not currently consider a unidirectional charger connected to a small generator (e.g., solar) can be classified as a small bidirectional unit as such an arrangement is not considered to function as a single entity.

Allowing for a wider range of technology configurations than is currently contemplated by AEMO may provide a way for it to apply technical performance standards for a range of EV charging configurations (such as ramp rates or disturbance-ride-through requirements), albeit limited to those participating under an SRA arrangement. Allowing the participation of such configurations as small bidirectional units, or any bidirectional *system* operating under common EMS, could also provide a pathway to scheduling. This could provide AEMO with greater operational visibility and control over EV fleet behaviours, and DER more broadly.

Scheduled Lite

In January 2023, AEMO lodged a rule change request to establish a Scheduled Lite Mechanism to enable the integration of price-responsive distributed resources into market scheduling processes, via a voluntary and flexible participation framework. The mechanism is intended to provide "*critical visibility and dispatchability services required to address complex and emerging power system challenges, avoiding the need for increasing reliance on intervention to manage system security and reliability; ultimately lowering costs to all consumers".*[66]

The rule change provides a vehicle by which AEMO may gain greater operational visibility and, predictability of EV charging infrastructure through central dispatch. This may include consideration of where and when AEMO may apply technical performance standards to different classes of customer assets. In its rule change request, AEMO proposed that '*traders participating in Visibility mode with other resources (e.g., non-scheduled generating units) will need to ensure they meet the relevant technical requirements, e.g., performance standards agreed with their connecting NSP and/or any conditions imposed by AEMO*' (p.37-38).

DER Technical Standards

In 2019, AEMO initiated a review of the performance of previous inverter standards to address emerging grid security concerns. This identified a series of changes and resulted in the development AS/NZ 4777.2:2020. Since December 2021, the NER has contained a glossary definition of DER Technical Standards with a singular requirement:

> *The requirements for embedded generating units under Australian Standard AS4777.2:2020 as in force from time to time.*

AS4777.2:2020 specifies '*device specifications, functionality, testing and compliance requirements for electrical safety and performance for inverters* [including] *electric vehicles that can operate as an energy source and energy storage system that can supply an electrical installation connected to the grid*.' [67]

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[64] AEMO is currently implementing the AEMC's Integrating Energy Storage Rule Change which created the Small Resource Aggregator category allowing for energy and ancillary service participation by DER aggregators.

[65] AEMC (2021) *Integrating energy storage systems into the NEM - Final amending rule*

[66] AEMO (2023) *Rule Change Request - Scheduled Lite Mechanism in the NEM*

[67] Standards Australia (2020) *AS/NZS 4777.2:2020 Grid connection of energy systems via inverters, Part 2: Inverter requirements*

The 2020 revision provides a range of system security measures that have been informed by AEMO's analysis of risks to power system security posed by growing levels of inverter-based generation. Key changes from the previous standard are:

- Previously, the Volt-Watt and Volt-Var set points needed to be set by the installer during commissioning. These set points are now built into the firmware of a compliant inverter. The installer only needs to set the relevant 'regional setting', and a compliant inverter will do the rest.
- Undervoltage ride through capability is now built into the firmware. This prevents inverters from switching off and disconnecting in response to low voltage events.

This NER requirement to meet DER Technical Standards is applied to DNSPs as terms and conditions they must include in any 'model standing offer' to a customer seeking to connect a new or replacement *embedded generating unit* (clause 5.A.B.2). An embedded generating unit is simply a generating unit connected to a distribution network (rather than transmission).

DNSPs generally establish whether an inverter is AS4777.2:2020 by reference to the Clean Energy Council's (CEC) Approved Inverter List however they are not bound to do this. For example, South Australia Power Networks (SAPN) has approved the connection of a bidirectional EV charger that has AS 4777.2:2020 test lab certification, without it being listed by the CEC.[68]

DER technical standard compliance challenges

The AEMC's *Final Report into Consumer Energy Resource Technical Standards* has noted that there has been significant non-compliance with this DER technical standard in the NEM. The AEMC has noted that non-compliance can occur across the life cycle of CER devices – manufacture and supply, installation and ongoing operations.[69]

The use of the NER to set DER Technical Standards has several significant and well-understood limitations that have undermined compliance rates to date:

1. The NER is not able to impose requirements directly on equipment manufacturers, product retailers or installers. It relies instead on the imposition of requirements on network businesses to enforce standards only at the point at which a customer seeks approval for connecting an embedded generator.
2. The obligation to meet DER Technical Standards ultimately resides with the customer when they accept a connection offer made by their local network operator. Customers have limited or no understanding of technical requirements that could impact power system security and are not well placed to monitor or provide assurance regarding technical standards compliance.
3. Networks may have limited capability and direct interest in enforcing technical standards that are not aligned with their specific operational requirements and commercial objectives.
4. The tools available to network businesses to manage cases of non-compliance is limited to denying or delaying connection. This is considered heavy handed due to the impact on customers and there is potential for reputational damage to the network if this were used too frequently.
5. The AER is not equipped to oversee or enforce compliance by networks (or other parties) in relation to small-scale installation matters. Instances of the AER initiating formal legal proceedings against breaches of the NER have been limited to non-compliance by large market participants where individual instances of non-compliance (e.g., with generator performance standards) are material to power system operation. By contrast, the risks associated with non-compliance by micro embedded generators generally arise only in aggregate.

These issues result in an *ineffective chain of accountability*, as described in Figure 10 below, and the requirements extend beyond the effective scope, and over the effective boundary, of national electricity market regulation. Overall, AEMO should consider that, while the AEMC is able to set new technical

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[68] Wallbox (accessed: 14 July 2023) *Vehicle-to-Grid (V2G) charging approved for South Australia*

[69] AEMC (2023) *Final Report - Review into consumer energy resources technical standards*

requirements for DER connecting to distribution networks, the NER is not well-suited to the imposition of broad-ranging appliance and equipment performance standards, regulating the activities of installers or product retailers or the ongoing activities of OEMs.

In its final Review, the AEMC recommends energy ministers lead the development of a national regulatory framework for CER technical standards and notes this process could draw on technical and other advice from the market bodies as needed.

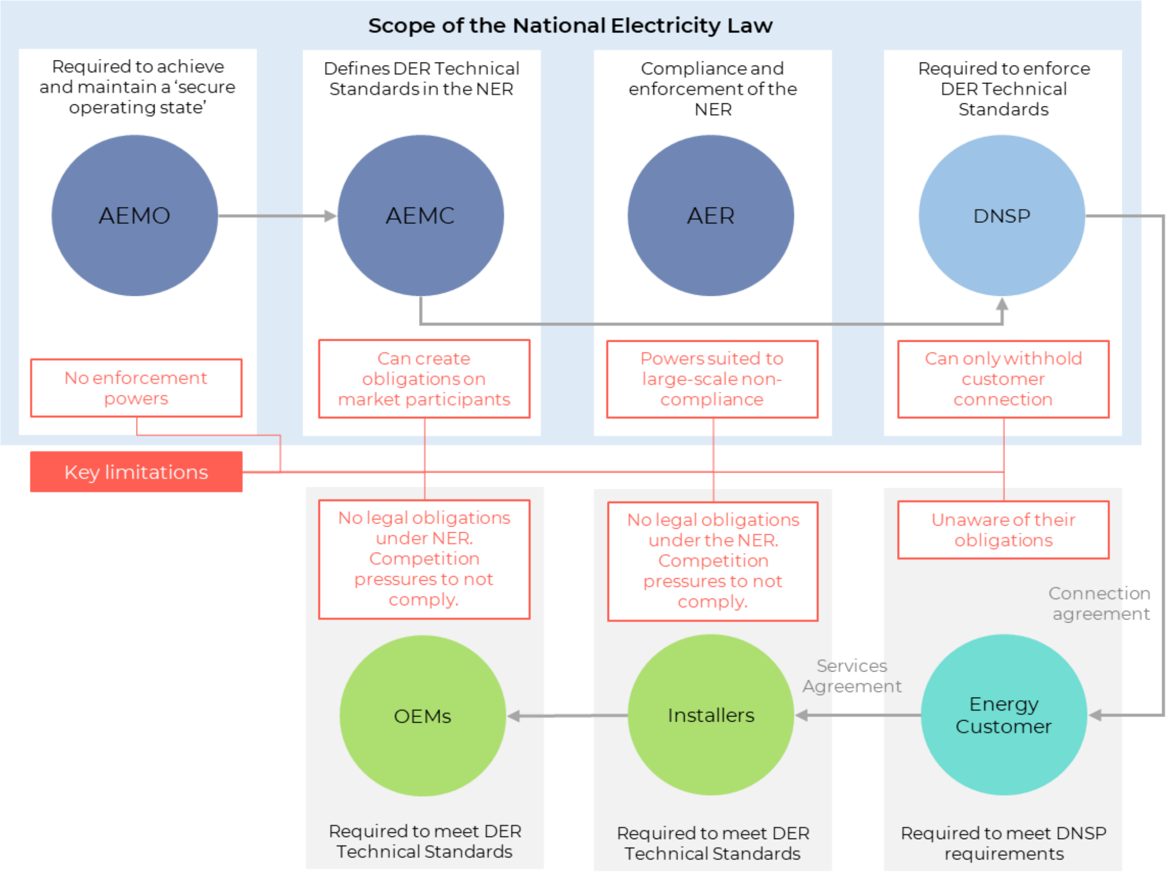

Figure 10 – The chain of accountability implicit in the NER imposition of DER Technical Standards.

Reforms to technical standards governance

The AEMC released its final report and recommendations for CER technical standards on 21 September 2023. Its report was based on the findings of consultation which explored challenges associated with the implementation of inverter standards (AS/NZS 4777.2) implications for compliance and enforcement arrangements and industry roles and responsibilities for broader CER technical standards including national and jurisdictional arrangements.[70]

The AEMC final review has recommended a series of immediate voluntary actions covering manufacture and supply, installation, and ongoing operations of inverter devices. The AEMC estimates implementation could result in half to almost all new devices in the NEM compliant with CER technical standards. In addition, compliance of existing devices is expected to improve by more than 40 per cent. The report also recognises jurisdictions still need to progress regulatory reform. The recommendations for immediate action under existing frameworks are unlikely to achieve near universal compliance due to the largely voluntary nature of implementation by industry.[71]

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[70] AEMC (2023) [Final Report - Review into consumer energy resources technical standards]().

[71] Ibid, p iii.

Jurisdictional Technical Regulation

In the formation of the NEM, it was agreed that the states and territories would broadly retain responsibility technical and safety regulation, in additional to any other matters not explicitly transferred to the national market bodies under national energy legislation.[72] These extend to a wide range of energy-related matters such as bushfire management, powerline safety, energy efficiency, consumer product performance and labelling, and local utility licencing.

Each state and territory regulate the installation and maintenance of energy-using equipment by electricians by reference to national standards (e.g., AS 3000:2018) or jurisdiction-specific codes and regulations. State and territory frameworks also extend some technical and safety obligations to owners of energy-using equipment or occupiers of premises where it is installed.

In its *Review into Consumer Energy Resources Technical Standards* for the AEMC, Baker McKenzie listed relevant jurisdictional legislation as follows.

- NSW – *Gas and Electricity (Consumer Safety) Act 2017*; *Gas and Electricity (Consumer Safety) Regulation 2018.*
- Victoria – *Electricity Safety Act 1998*; Electricity Safety (General) Regulations 2019; *Essential Services Commission Act 2001*; *Electricity Industry Act 2000*; *Electricity Distribution Code of Practice.*
- South Australia – *Electricity Act 1996*; *Electricity (General) Regulations 2012*; *Electricity Distribution Code*; *Technical Regulator Guidelines.*
- Queensland – *Electricity Act 1994*; *Electrical Safety Act 2002; Electricity Regulation 2006*; *Electrical Safety Regulation 2013.*
- Australian Capital Territory – *Electricity Safety Act 1971*.
- Tasmania – *Electricity Supply Industry Act 1995*; *Tasmanian Electricity Code*; *Electricity Industry Safety and Administration Act 1997*; noting the Electricity Safety Act 2022 will consolidate the Tasmanian framework once in force.
- Northern Territory – *Electricity Reform Act 2000*; noting the Electrical Safety Act 2022 (NT) will consolidate the Northern Territory framework once in force.
- Western Australia – *Electricity Act 1945*; *Electricity Regulations 1947*; *Electricity (Licensing) Regulations 1991*; *WA Electrical Requirements*.[73]

Licensing schemes for electricians are a primary compliance tool for jurisdictional safety requirements. Non-compliance with relevant regulations and codes can result in severe penalties including a loss of licence. Compliance is supported by training and accreditation regimes, site inspection and certification requirements, backed up with compliance assurance and enforcement procedures. While these elements are present in all jurisdictions, the details and consistency of application of these program elements vary greatly. Electrical safety regulation must co-exist with broader workplace safety requirements.

There have been numerous, but isolated, instances where jurisdictional technical regulation has extended to the application of DER Technical Standards. A good example of this is the South Australian Office of the Technical Regulator which has set requirements for DER interoperability[74] and control to manage acute power system management challenges (solar backstop)[75]. In some cases, these requirements have responded to specific risks identified by AEMO. In others, these have more reflected jurisdictional policy settings.

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[72] AEMA (as amended December 2013) *Australian Energy Market Agreement*

[73] Baker McKenzie (2023) *Review into consumer energy resources technical standards.* This report also provides a summary of relevant regulatory authorities, tools to monitor compliance and enforcement/penalty regimes.

[74] For example, *OTR's requirements for EVSE interoperability* or *OTR's remote communications capabilities for inverters*

[75] SA Department of Energy and Mining (accessed 14 July 2023) *Regulatory changes for smarter homes*

Imposing equipment technical standards through jurisdictional technical legislation

The diversity of jurisdictional contexts and interests, and the general focus of jurisdictional regulators on safety, provides a challenge to using jurisdictional technical regulation to support the implementation of technical standards to promote power system security outcomes.

The South Australian Smarter Homes (solar backstop) scheme provides an exception to this. This outcome was enabled by the significant and near-term challenges the scheme sought to address. It was also assisted by the limited scope of the requirement which related to the curtailment of electricity exports, and did not impact customer loads, as would be the case for EVSE and other relevant electronic loads.

Jurisdictional technical regulation is not considered an appropriate long-term pathway for the application of performance standards for EVSE, or other electronic loads, to manage long-run power system risks.

Incentives schemes

Small-scale Renewable Energy Scheme

The Small-scale Renewable Energy Scheme (SRES) provides financial incentives for the installation of small renewable energy systems including solar PV and heat pump water heaters. It is administered by the Australian Government Clean Energy Regulator (CER). From April 2022, eligible installations must only use inverters from the Clean Energy Council’s Approved Inverter List. Prior to this, the CER set out a range of specific standards that must be met for eligible installations (e.g., AS 4777, and AS 3000). The CER specifically refers to the CEC’s Approved Inverter List to demonstrate AS4777.2:2020 compliance.

The SRES is due to end in 2030 and the incentives decline each year until then. It is also important to note that, for the purposes of this study, SRES eligibility requirements apply only to *renewable energy generating systems* and this excludes batteries, EV chargers or any other loads. As such, SRES is a not a viable option for the application of Technical Standards for EV chargers (uni or bidirectional) or other electronic loads.

ARENA

ARENA provides funding for pre and early commercial demonstration projects. It administers the $500 million Driving the Nation program which provides support for business fleets, new technologies for heavy and long-distance vehicles, public charging and hydrogen refuelling stations and smart charging.

ARENA has not previously sought to advance the adoption of voluntary standards through its funding criteria. Its funding programs are also generally short lived and focussed on early-stage commercialisation, and so do not provide a suitable lever for broad-based standards adoption.

Jurisdictional EV uptake incentives

Various incentive schemes have arisen to promote consumer uptake of EVs. Nationally, these include a higher luxury tax threshold for EVs, and further incentives may be implemented under the proposed National EV Strategy.[76] States and territories also offer a range of incentives such as rebates, stamp duty and registration discounts or waivers.[77]

The life of these incentive schemes will be impacted by government decisions on the extent to which they are needed to promote EV uptake and are therefore likely to be weighted to early stages of EV market development. They are therefore not considered to provide a suitable lever for broad-based standards adoption on an ongoing basis.

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[76] DECCEW (accessed 14 July 2023) *The National Electric Vehicle Strategy*

[77] The NRMA tracks government incentives for EVs: *Incentives for EV drivers in Australia*

Interoperability principles for public funding of EVSE

The ESB has recommended that Australian governments work together to develop National Principles for Minimum Interoperability Features for Publicly Funded Charging Infrastructure. This is intended to help future-proof publicly funded infrastructure, enhance consumer experience, and align industry incentives with shared policy objectives, and provide a flexible transitional arrangement while mandatory minimum standards are developed and implemented.

While the scope of this project excludes broader interoperability considerations, several of the risks identified in Chapter Potential risks to system security 7 can be addressed via specific cyber security controls being implemented by parties with operational control of EVSE, such as charge point operators and aggregators. National principles for public funding of EVSE could, for example, provide a mechanism to ensure early deployments of EVSE adopt minimum standards for remote communications, such as public key infrastructure (PKI) and/or that Certificate Authorities have minimum levels of accreditation (e.g., Gatekeeper[78]).

A further benefit of this approach could be building industry capacity in relation to good practice cyber security, on a voluntary basis, while a more enduring framework for mandatory requirements are developed.

Greenhouse and Energy Minimum Standards

The *Greenhouse and Energy Minimum Standards Act 2012* (GEMS Act) came into effect in 2012, creating a national framework for product energy efficiency in Australia, including Minimum Energy Performance Standards and Energy Rating Labels (energy star ratings). It covers a range of consumer products (such as fridges and televisions) as well as industrial equipment (e.g., distribution transformers and electric motors).[79]

Determinations are made by the Australian Government Energy Minister, with consent by a quorum of states and territories. The GEMS Act is administered Greenhouse and Energy Minimum Standards Regulator (GEMS Regulator) which is based in the Australian Government Department of Climate Change, Energy, the Environment and Water (DECCEW).

A review of the legislation in 2019 recommended the scheme be expanded to new high energy using products that are not currently regulated in Australia. Review findings are being implemented in two tranches:

1. The *Greenhouse and Energy Minimum Standards Amendment (Administrative Changes) Bill 2023* will '*improve the implementation of the Act through improving regulator performance and reducing administrative burden*.'[80]
2. A further review of the scope of the GEMS Act is expected to commence in the second half of 2023. This will explore the scope of requirements and product coverage, including its extension to EVSE.

Following this second review, the legislation *may* be amended to include energy efficiency and related performance requirements for EVSE and other consumer energy resources.

GEMS as a pathway for the implementation of grid performance standards

Overall, the GEMS Act provides a possible vehicle for the imposition of grid performance standards for EVSE and other electronic devices. This is subject to the GEMS Act Review, which will commence in 2023, and subsequent and substantive legislative changes to provide the GEMS Regulator and Energy Minister

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[78] Digital Transformation Agency (accessed 21 August 2023) *Gatekeeper Public Key Infrastructure Framework*

[79] Australian Government (accessed 14 July 2023) *Regulated products*

[80] The Parliament of the Commonwealth of Australia (2023) *Greenhouse and Energy Minimum Standards Amendment (Administrative Changes) Bill 2023*

greater scope for flexibility in relation to product requirements that can be imposed. The objects of the GEMS Act are closely associated with Australia’s international climate commitments[81]. As such, it is likely that any new grid performance standards will need to be justified in relation to Australia’s broader energy transition, and how the standards support renewables uptake and reduced emissions. This reform could also be evaluated against other long-term regulatory reform alternatives to improve the governance of CER technical standards.

Proposals for a new national technical regulator

Several recent ESB and market body consultations have highlighted the deficiencies of current national regulatory frameworks as discussed above (p.48).

Several stakeholders have noted the potential for a new national technical regulator to rationalise and enhance technical standards requirements for DER and improve compliance outcomes. In its *Draft Review into Consumer Energy Resources Technical Standards*, the AEMC has noted ‘*some stakeholders have suggested creating a national technical regulator to support improved compliance with DER technical standards. However, to date, there is little consensus on the model, functions, and implementation approach for such an entity*’. Accordingly, the Commission considered ‘*more work is needed to determine if reform of national technical regulation is needed and, if so, the most appropriate reform model’*.[82] This option was included as one of the four reform options presented in the AEMC’s final report.

Overall, enX considers that the highest value proposition for a new national technical regulator relates to governing the conduct of installers and new energy service providers, complementing the AER’s current economic regulatory functions. A new national technical regulator could pick up on some of the current functions of the Clean Energy Regulator regarding solar installer and solar retailer accreditation, as the SRES scheme comes to an end. The development of a new national technical regulatory authority is greatly complicated by the many potential interfaces with jurisdictional technical regulation, and it is therefore not a near-term prospect.

A new national technical regulator could support compliance with DER Technical Standards implemented under the NER, *as it is impacted by the conduct of installers and new energy service providers*. The GEMS Act already provides an effective framework for applying minimum standards and product information to consumers and appears the most appropriate mechanism for the imposition of new equipment performance standards. It is possible that a new national technical regulator could subsume, or more likely sit alongside, the GEMS Regulator.

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[81] Australian Government (2012) *Greenhouse and Energy Minimum Standards Act 2012*, Division 3

[82] AEMC (2023) *Final Report - Review into consumer energy resources technical standards*

7. POTENTIAL RISKS TO SYSTEM SECURITY

This chapter explores a range of theoretical risks to bulk power system security associated with a very high uptake of electric vehicles.

The focus on the bulk power system necessitates consideration of issues that may originate on the distribution network, but only where the aggregated effect is sufficient to impact transmission.

Some of the risks to power system security are common to modern electronic loads while others may be unique to EV smart charging functionality or the design characteristics of EVSE. Overall, none of these risks should present a barrier to the electrification of Australia's vehicle fleet and each risk is considered to have a logical mitigation strategy that can be developed and implemented prior to it becoming a significant concern.

These risks also need to be understood in the context of the broader transformation of the power system, including higher penetrations of electronic loads and DER. Broader challenges include:

- Low system strength and inertia – High instantaneous penetrations of inverter-based generation and load are associated with low system strength and inertia, contributing to voltage wave form instability and high rates of change of frequency.
- Primary frequency response limitations – While most large electronic loads are capable of quality frequency response, limitations in some EV-EVSE technology stacks (latencies, combined with consumer usage preferences) may reduce the extent to which these resources can provide primary frequency response/fast FCAS.
- Voltage control – AEMO's Engineering Framework identifies the risk of voltage swings triggering disconnection of electronic loads due to the design of equipment electrical protection settings.
- Frequency management – AEMO's Engineering Framework also identifies the risk of load disconnection (such as EVs) during frequency disturbances, with potentially large aggregate impact if not managed.
- Diversity Destruction - High-penetrations of unscheduled, price responsive DER/EVs, could create step changes in generation or demand impacting voltage and frequency, as well as oscillatory instability through 'closed-loop' price-demand interactions.
- Ramp rates – The above effects may be compounded by unconstrained ramping of unscheduled and behind-the-meter resources.
- Cyber risks – Orchestrated DER (including EVs) have inherent vulnerability to cyber-attack. Threat vectors include aggregator, charge point operator and automaker communications channels.
- System restart – system restoration following an outage is a very rare situation at the scale of the bulk power system, however it is a challenging process that may become more difficult with connected smart charging systems and large loads with 'cold load pickup' characteristics.

Specific technical challenges that have been considered in this risk analysis include:

- Cold load pickup
- Control system reboot
- Constant power loads
- Control primacy clash
- Control system interactions
- Delayed return (post-fault)
- Dependency on communication
- Failure of fault ride-through
- Lack of visibility (real-time and post-event)
- Load response characteristic
- Malicious actors (cyber-attack)
- Panic response
- Phase-Locked Loop unlock
- Preparation for / response to event
- Randomised control
- Reduced effectiveness of load shedding
- RoCoF tripping
- Software update / error
- Software-controlled load pick-up
- Stable island formation (V2G)
- Time of use tariff load steps
- Unpredictable load recovery
- Voltage tripping
- Misalignment of directional charging response

Behaviour characterisation

EV chargers may exhibit a range of behaviours, however with respect to the bulk power system the three most recognisable forms of response, in aggregate, are step, ramp and oscillation. These types of behaviour are shown below in Figure 11. While these figures are only illustrative, they can be helpful when thinking about risks that may arise and the controls that may be necessary to mitigate them.

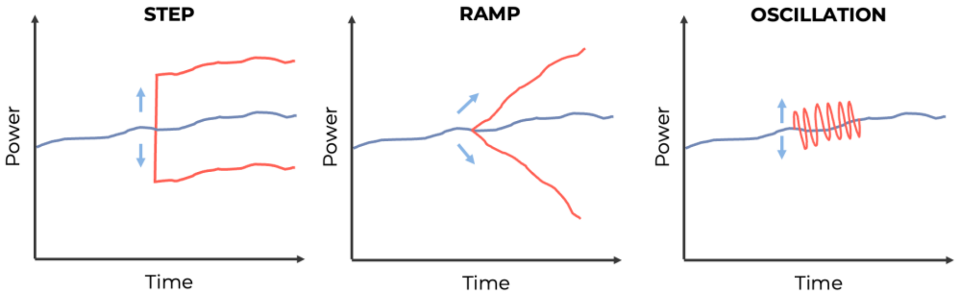

Figure 11 – Step, Ramp and Oscillation behaviour.

Quantifying power system impacts

The potential size of EV load profiles

The risks associated with EV charging are strongly related to their share of instantaneous demand. This is impacted by the rate and extent of EV uptake in Australia and the coincidence of load across potentially millions of individual equipment endpoints.

The *Input and Assumptions and Workbook* from the AEMO 2022 Integrated System Plan (ISP) and the *Detailed Electric Vehicle Databook* provide estimates of potential vehicle uptake and forecast daily load profiles for EV charging developed by CSIRO.[83]

Data on the number of EVs, charge type and profiles in 2030-31 were used to assess possible ‘near term’ charging demand in the NEM for residential, commercial and industrial sectors.

North America, Europe and the UK are focused on the 2030 timeframe due to policy action and industry goal setting to align with net zero objectives. Public government and industry policy considers that the transport sector will play an important role in decarbonisation, and that this will necessitate a rapid shift to EVs and supporting infrastructure. This represents an unprecedented transition for the automotive sector, however targets for EVs and bans on ICE vehicles have nonetheless been established by statutory instruments. This is in turn driving concerted efforts to assess infrastructure needs, and establish and align technical settings (including grid integration standards and guidance for EV chargers) over this timeframe,

Potential charging profiles, derived from the 2022 ISP, are shown below in Figure 12. It shows that as early as 2031, EV charging could constitute a multi-gigawatt load in the NEM at various times of the day.

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[83] AEMO (2022) *Current inputs, assumptions and scenarios*

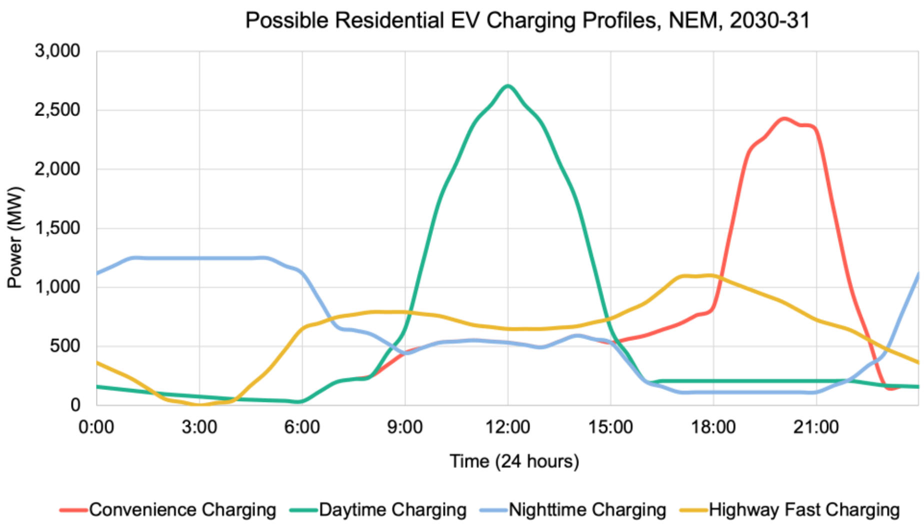

Figure 12 – Potential EV weekday charging profiles.

Charging for the EV fleet seen here may represent a significant load in 2030, however as shown in Figure 13 below it is likely to be very material to power system operations in 2040. This illustrates for context the importance of considering these matters strategically for the long-term interest of power system management.

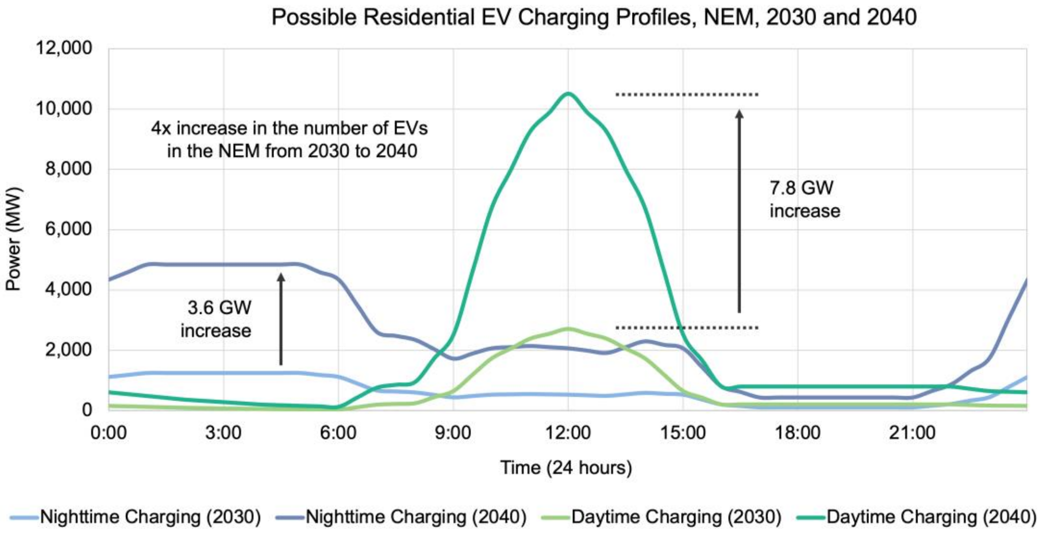

Figure 13 – Charging for the EV fleet, which may represent a significant load in 2030, is likely to be very material to power system operations in 2040. Only daytime and nighttime profiles are shown for the purposes of illustrating high and low magnitudes.

Breakdown of the future EV charger fleet

NREL, in collaboration with the Joint Office of Energy and Transportation of the United States Government, published a quantitative assessment for a 2030 national charging network capable of supporting the transition to EVs in the US.[84] This study considered consumer preferences and transportation models to estimate the numbers of public and private charging ports required per EV. This information has been combined with AEMO ISP data to assess the possible charger fleet capacity in 2030-31.

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[84] NREL (2023) *Building the 2030 National Charging Network*

A breakdown of different charging types by rated capacity is shown in

Figure 14. This illustrates the importance of considering risks associated with private chargers, as they are expected to be most of the EV charger fleet.

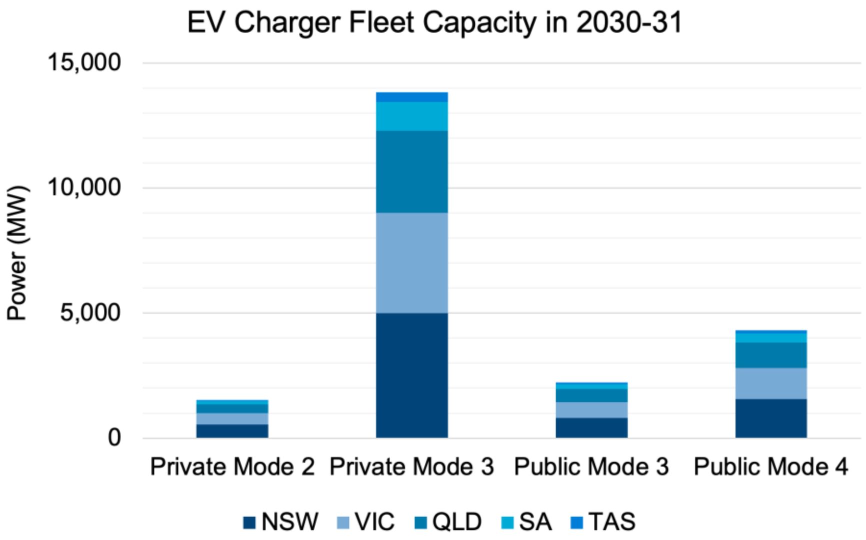

Figure 14 – Estimated sum of the rated capacity of the EV charger fleet in the NEM in 2030-31, showing the primacy of private chargers.

Risk assessment framework

Approach to risk definition and evaluation

Risks are generally defined as a function of their probability and severity, with five increments of each, and five overall risk ratings.

A 5 x 5 matrix was used for assessing potential risks to power system security associated with EV charging in the NEM. Low-rated risks may fall within the risk tolerance of power system operation, while high-rated risks represent an eventuality outside risk tolerance without additional controls / treatment.

Table 3 – Risk rating definitions.

Risk rating	Definition
Very Low	Risk mitigation is **optional**.
Low	Risk mitigation is **optional**.
Medium	Risk mitigation is **desirable**.
High	Risk mitigation is **essential**.
Very High	Risk mitigation is **essential**.

Risk severity definitions

Power system impacts can have a range of dimensions of impact that may be valued differently by different stakeholders. These may include:

- Affected load (MW)
- Affected demand (MWh)
- Affected customers
- Time of outage

- Operating state (Secure/Insecure)
- Damage caused ($)
- Frequency deviation (Hz)

For the purposes of this study, we have applied the risk severity definitions set out in Table 4.

Table 4 – Risk severity definitions

Severity	Definition
Negligible	Impact on the bulk power system is limited but may affect **distribution networks**.
Minor	Impact on the bulk power system within the parameters of **normal operation**.
Significant	Impact on the bulk power system that impacts **ancillary service requirements**.
Major	Impact on the bulk power system that requires **involuntary load shedding**.
Severe	Impact on the bulk power system that requires **system restart**.

Risk probability definitions

Occurrences of an event may range from a regular experience to something that may never occur but potentially should be planned for. Probability definitions are listed in Table 5. Given inherent difficulties in predicting the likelihood of uncertain events these definitions should be taken as illustrative and largely relative.

Table 5 – Risk probability definitions

Probability	Definition
Rare	Event is unlikely to occur more than **once in 20 years**
Unlikely	Event is unlikely to occur more than **once in 10 years**
Possible	Event is unlikely to occur more than **once in 5 years**
Likely	Event is unlikely to occur more than **once in 1 year**
Almost Certain	Event is unlikely to occur more than **once in 1 month**

Literature reviews, semi-structured interviews and workshops were used to initially locate and characterise risks. A risk assessment was then iterated with AEMO and Expert Advisory Group members to achieve consensus on risk definition, probability, and severity ratings.

Risks were categorised into two broad types – *autonomous response* and *application control*, reflecting the underlying technology conditions that give rise to the risk materialising, and where risk is located in the EV charging technology stack*:*

- Autonomous responses are responses inherent to the operation of the equipment, typically due to firmware programming of power mode and/or protection settings.
- Application controls are responses that require an exogenous control signal such as a charging instruction from an energy management system or OEM in response to a market price or operating envelope.

Summary of power system risk assessment results

Table 6 provides a list of key risks and their overall risk rating (prior to mitigation). This shows that disturbance ride-through issues, while important, are not considered to be the highest priority in the near term. Risks such as this, related to the inherent response of an EV charger were broadly seen as more likely to impact the distribution network, and where they do impact the bulk power system, this would occur over longer timeframes. Risks related to application control are considered more likely to have major or severe impacts on the bulk power system, at least in the near term, if not mitigated.

Each of these risks is described in more detail in the sections below.

Table 6 – Risk assessment summary.

Type	**Summary**	**Ratings**
Automation Layer		
Voltage disturbance	EV chargers disconnect due to a disturbance and the power system experiences a load step, voltage cascade, frequency excursion or instability.	Low to Medium
Voltage collapse	EV chargers exhibit constant power behaviour, due to OEM software implementation of EV-EVSE communications standards, reducing stability and leading to voltage collapse.	Medium
Frequency disturbance	EV chargers represent a significant proportion of system demand and do not provide load relief, resulting in instability and involuntary load shedding.	Medium
Application Layer		
Cyber security	CPO, OEM or Aggregator IT infrastructure is compromised, and the power system to experience a very large load step causing widespread power loss.	Medium to Very High
Software management	A flawed EV charger software patch is deployed, resulting in an error that causes very large load step down and the activation of protection systems.	Very High
Communications loss	The loss of communications for EVSE in a region means smart charging reverts to offline control mode(s) resulting in a very large load step up.	Very High
Price response	EV chargers switch on and off repeatedly in response to changes in dynamic pricing, and the power system experience closed-loop price-demand interactions.	High
Event response	EV chargers switch on in aggregate in response to a notice or emergency alert, and involuntary load shedding is required to manage supply and demand.	High
System restart	EV chargers reconnect to distribution networks after an outage with higher load, which challenges recovery and significantly delays restoration.	Low
Network management	EV chargers switch on and off repeatedly in response to changes in dynamic operating envelopes, and the power system experience closed-loop interactions.	Medium
Diversity destruction	Price responsive EV chargers switch on/off or change charge direction simultaneously in aggregate, and the power system experiences an extreme Rate of Change of Frequency (RoCoF) and/or significant frequency excursion.	Very High

Automation Layer risks

Risks related to a response attributable to the Automation Layer of EV chargers concern equipment disconnection (and a corresponding load step down in load) in response to a disturbance in a NEM region. Like other electronic loads, automation risks typically originate in the design and programming of the charger, whether that is onboard (DC charging) or offboard (AC charging). These risks can be reduced with conscious design decisions in the development of the charging technology.

Automation layer risks relates primarily to the equipment's ability to ride-through a voltage or frequency disturbance, rather than disconnect. Consistent with prior studies on this issue, this would be most problematic where many chargers are operating simultaneously and represent a large share of instantaneous demand.

This is similar to challenges with managing embedded generating units that has been mitigated by inverter standards. Indeed by 2030-31 the EV charger capacity in the NEM could be comparable to the installed capacity of BTM battery or solar, as shown below in Figure 15

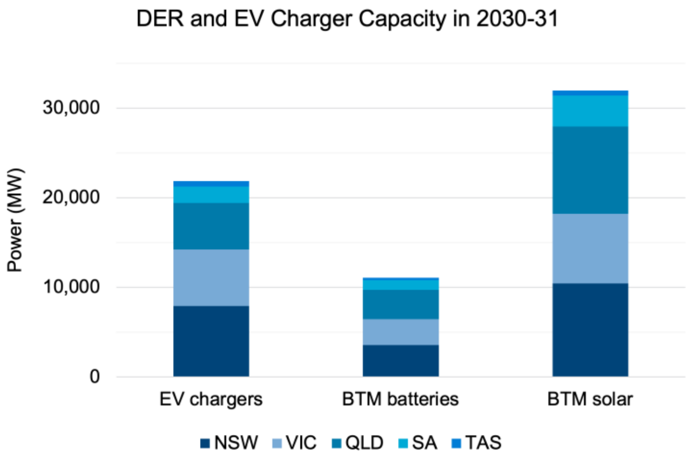

Figure 15 – EV charger capacity could be comparable to behind-the-meter and rooftop solar PV capacity in the NEM in 2030-31.

Figure 16 below illustrates an extreme scenario where a third of EV chargers disconnect under the residential forecast for residential EVs in NSW in 2030-31. The magnitude could be 2.5 times larger for a frequency disturbance across the NEM as a whole in the same time period, and 4 times larger again in 2040-41.

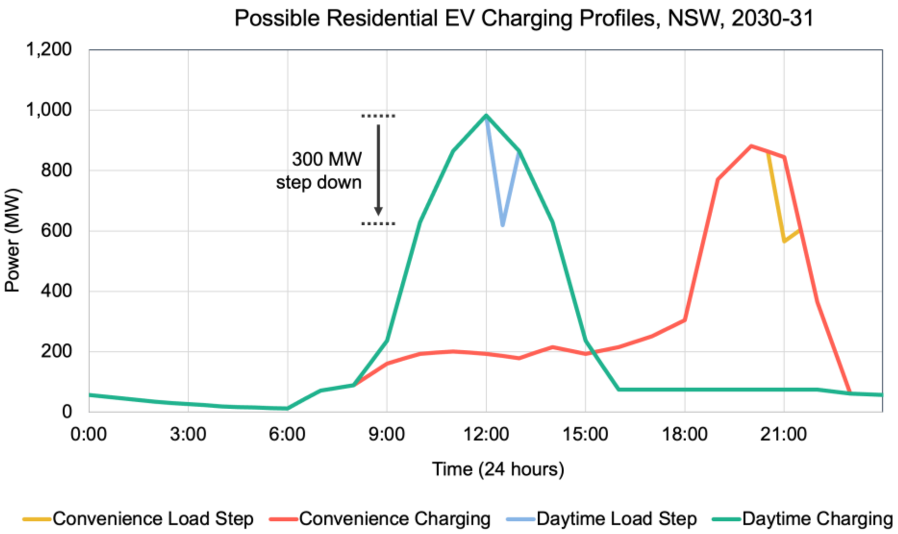

Figure 16 – Illustrative load step down as one third of charging EVs in a NEM region disconnect in response to a voltage or frequency disturbance.

A possible load step in this scenario is significant, broadly equal to the loss of a large generating unit in some regions and consistent with AEMO's definition of a 'credible contingency event' used to inform FCAS procurement volumes. A counter-productive response from EV chargers in response to a voltage drop or low frequency excursion may lead to further loss of load resulting in the need to deploy emergency measures such as UFLS or regional islanding.

This type of scenario is the basis for exploring the various risks in the automation layer. The likelihood, possible causes and effects of specific risks regarding voltage disturbances, frequency disturbance and system restart procedures are outlined in more detail below.

Voltage disturbance risks

Quality EV chargers can reasonably be expected to withstand moderate, short voltage disturbances, consistent with equipment design imperatives to maintain service uptime (and customer utility) through normal voltage conditions where a sag or swell does not dip below 0.8 pu or exceed 1.1 pu respectively. Given that voltage ride-through is not regulated for consumer appliances such as EV chargers, it is possible that some manufacturers may tighten operational voltage bands, either inadvertently, or for device protection. This may result in some chargers disconnecting more frequently and under less severe voltage disturbance conditions. In this case, the power system could experience a load step down in response to a voltage sag or swell, undermining secure power system operation.

As discussed in Chapter 5, SAE J2894 is a Recommend Practice that is evolving with industry consultation, research and product development. It is not clear what proportion of products on the market are following this guidance, however it has helped guide elements of this risk assessment. This has been supplemented with local equipment testing data, discussed in Chapter 2, and expert consultation to characterise disturbances in terms of sign (under/over), magnitude and duration.

At the transmission-scale, these risks are largely theoretical and have not been observed at scale for electronic loads among the experts and international literature reviewed for this project. In theory, however, this risk could become material overtime as electronic loads become a larger share of instantaneous demand. These issues are well described in the Sygensys (UK) and NERC (US) reports (see pages 32-33) however further work is required to accurately quantify the potential likelihood and severity of these risks in the NEM. Further laboratory testing of appliances, and customer load monitoring is needed to develop and maintain a representative view of equipment types, and their response to voltage disturbances, as electronic equipment stocks and loads change over time.

Table 7 provides a summary of seven key voltage disturbance risks identified through our research and consultation process, including two “low” and five “medium” risks.

Overall, our assessment indicates that the impact of these risks on the bulk power system is likely to be limited in the period to 2030-31. Where it does impact system operation at the transmission-scale, it will probably be managed by FCAS. This assessment suggests that it is, however, likely to represent a significant challenge at the distribution-level system operations. This would benefit from a strategic, nationally consistent approach to the technical regulation of EV charging equipment. A collaborative program will mitigate against these risks becoming more severe, and avoid inefficient costs associated with disparate requirements.

Table 7 – Voltage disturbance risks

#	Cause	Effect	Risk assessment
1.1.1	EV chargers do not withstand a moderate, short voltage disturbance (0.5 pu sag) as charge controllers prioritise cost over power system security.	The power system experiences a load step down as a small fraction of EV charging load disconnects simultaneously on a distribution network.	Probability = Unlikely Severity = Minor **Risk = Low**
1.1.2	EV chargers do not withstand a moderate, extended voltage disturbance (0.5 pu sag) as charge controllers prioritise cost over power system security.	The power system becomes unstable due to an over-voltage cascade which results in widespread loss of power as protection systems activate.	Probability = Unlikely Severity = Minor **Risk = Low**
1.1.3	EV chargers do not withstand a moderate, extended voltage disturbance (0.5 pu sag) as charge controllers prioritise cost over power system security.	The power system experiences a load step down which results in over-frequency conditions that requires frequency control ancillary services to manage.	Probability = Unlikely Severity = Significant **Risk = Medium**
1.1.4	EV chargers remain disconnected after a severe, extended voltage disturbance (0.3 pu sag) as charge controllers prioritise cost over power system security.	The power system experiences a load step down as a large fraction of EV charging load disconnects simultaneously on a distribution network.	Probability = Possible Severity = Significant **Risk = Medium**
1.1.5	Embedded generation disconnects because of a fault before EV charger load due to standards for the grid connection of energy systems via inverters.	The power system experiences fault-induced delayed voltage recovery and activates involuntary load shedding to arrest an under-voltage cascade.	Probability = Possible Severity = Significant **Risk = Medium**
1.1.6	EV chargers disconnect due to a severe, extended voltage disturbance (1.2 pu swell) and require operator intervention to reconnect.	The power system becomes unstable due to an over-voltage cascade which results in widespread loss of power as protection systems activate.	Probability = Unlikely Severity = Significant **Risk = Medium**
1.1.7	EV chargers exhibit constant power behaviour due to OEM software implementation of EV-EVSE standards.	The power system becomes unstable resulting in the activation of involuntary load shedding to manage supply and demand imbalance.	Probability = Possible Severity = Significant **Risk = Medium**

Risk 1.1.1 describes the risk associated with a short voltage disturbance on the distribution network. Local equipment testing suggests equipment that prioritises cost minimisation could disconnect in response to a voltage sag of 0.5 pu, because inverter over-current protection and under-voltage detection schemes work

in tandem for faster disconnection to protect the appliance.[85] These chargers would probably represent a small share of those on the system, and so a small step down of the load is observed on the power system. This could impact the system at a distribution level however it is probably insignificant at transmission level – 'minor' severity.

There are active and passive measures on the grid to deal with such voltage disturbances. When voltage sag is detected on the network, the network protection systems for fault clearing, line recloser for example, is operated very quickly (in about 2.5 cycles) to restore the voltage back to normal[86]. Even so, non-credible contingency events do occur at the transmission level – 15 events have been observed in the past 5 years.[87] The probability of a moderate voltage disturbance in this category propagating to the bulk power system and impacting the operation at transmission level could thus be considered 'likely'. The probability of this occurring due to EV chargers in 2030, however, is considered 'unlikely'.

Risk 1.1.2 describes a moderate voltage disturbance for a longer duration than described in *Risk 1.1.1.* Assuming the voltage disturbance lasts longer than 10 seconds, an AS/NZS 4777.2:2020 compliant inverter must disconnect for a maximum of 11 seconds. Local equipment testing showed an EV charger may disconnect for 7 seconds.[88] This reduces the active load power on the network, which is desirable, however when sufficient EVSE load drops over voltages occur. Where sufficient numbers of EV chargers disconnect, this could lead to unacceptable voltage ranges (>1.1pu) which causes widespread disruptions on the network.

Reconnection can further amplify over voltage issues and cascading faults. This true for EV chargers with grid following inverters, where during reconnection when the inverter tries to synchronise the grid voltage waveform. The pre-fault and post fault differences in phase angle is so large that the measurement might have inaccuracies[89]. This impacts injection of current, triggering errors that further impact the voltage waveform. This can cascade and ultimately lead to widespread disruptions and the activation of protection systems. The probability of this impacting bulk power system is still considered 'unlikely', however, and it would probably be limited to a distribution network – a 'minor' severity.

Risk 1.1.3 describes risk of over-frequency condition for a load step down. For example, a trip of the largest load on the network (>1000MW for example) can cause over frequency (approx. 51Hz depending on inertia value MWs/Hz) issues. Research by NREL characterised extreme frequency events as low probability and high consequence events.[90] Furthermore, *Frequency Risk and Control Report* by UK national grid identified that the likelihood of over frequency risks (50.5>Hz) of any duration is 1 in 1,100 years.[91] In Australia, Inverters are required (as per 4777.2:2020) to have a protective function limit value for over frequency (52>Hz) with a maximum disconnection of 2 seconds. Load drop of EVSEs on the NEM leading to over frequency of >52Hz is unlikely at this stage but the growing demand of EVs on the network might pose a threat in the future.

EVSE can present such risks when large volume is connected to the grid, which would require FCAS to manage – a 'significant' impact. The probability of this impacting the bulk power system is 'unlikely', however, because of the scale of EV penetration forecast for the NEM in 2030 and the presence of various protection mechanisms integrated into power networks.

Risk 1.1.4 describes the risk associated witha severe voltage disturbance in the form of a sag down to 30% of the nominal value (0.3 pu). Local equipment testing found that a charger may disconnect for an extended

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[85] D. Turcotte and F. Katiraei, *Fault contribution of grid-connected inverters*, *2009 IEEE Electrical Power & Energy Conference (EPEC)*, Montreal, QC, Canada, 2009, pp. 1-5, DOI: 10.1109/EPEC.2009.5420365.

[86] Roger C. Dungan et.al, Electrical Power Systems Quality, Second Edition - McGraw Hill

[87] AEMO *Power system operating incident reports* *Accessed 21/8/2023*

[88] APQRC (2023) GPST DER and Stability Stage 2 Final Report

[89] AEMO (2020) *System strength in the NEM explained*

[90] NREL (2017) *Grid Frequency Extreme Event Analysis and Modelling*

[91] National Grid ESO (2021) *Frequency Risk and Control Report V2*

period of time (32 seconds) in this scenario. Where this occurs, the power system could experience a load step down as a large fraction of EV charging load disconnects simultaneously on a distribution network. A deeper voltage disturbance like this is considered more likely to impact the transmission-level than a more moderate sag, and as such has been assigned a ‘possible’ probability. The impact is still considered ‘significant’ though due to the limited uptake of EVs forecast in the period to 2030-31.

Risk 1.1.5 describes the risk inherent in the interplay between distributed load and generation. Ideally, to support system stability, load will disconnect before generation in in the event of under-voltage conditions and after generation during over-voltage conditions. Currently, however, embedded generation is subject to stricter technical regulation that converter-based loads such as EV chargers.

This introduces the risk that embedded generation disconnects because of a fault before EV charger load due to standards for the grid connection of energy systems via inverters. This would be caused by solar PV or battery inverters disconnecting in accordance with AS/NZS 4777.2, before unidirectional EV chargers which are not subject to the same standard.

In this situation, the power system would experience fault-induced delayed voltage recovery. This could require the activation of involuntary load shedding to arrest an under-voltage cascade. The impact on the bulk power system, however, is more likely to be limited to control via ancillary services – a ‘possible’ and ‘significant’ risk.

Risk 1.1.6 describes the risk inherent in coincident tripping due to high voltages. Traditional loads naturally survive brief over-voltages, however new converter-based equipment relies on semiconductor devices which are more sensitive to damage under these conditions. As a result, equipment like this, including EV chargers, will typically include over-voltage protection sometimes referred to as Over-Voltage Lock-Out (OVLO). This can require operator intervention to reset a physical or digital switch, and thus may stay offline for an extended period of time.

If a large number of EV chargers, representing a significant share of system load, trip simultaneously in this manner it can act to exacerbate the original issue. That is, a reduction in load further increases voltage, and thus trips off more load, which creates a ‘snowball’ effect. This is known as a cascade, and in this instance and over-voltage cascade.

A voltage increase (swell) to 20% above the nominal value (1.2 pu) exceeds the AC service limits for equipment such as EV chargers.[92] This would not be a common occurrence but can reasonably be expected to occur in the span of years of power system operation - it is thus considered ‘unlikely’. The power system instability due to an over-voltage cascade could require ancillary services to stop and the impact is hence considered ‘significant’.

Risk 1.1.7 describes the risk discussed in Chapter 7, where EV charging is moving towards charge session management based on high-level communications between the EV and EVSE. This provides the opportunity to regulate EV charging in a range of ways, however in the absence of guidance from power system operators this is trending towards constant power behaviour. EV chargers operating in constant power mode exacerbates disturbances. In response to voltage drop on the network, the EV charger will increase current consumption to maintain constant power to the EV, which aggravates voltage drop ultimately leading to a voltage collapse. As shown in Figure 16 (p.62), this is the opposite of the type of traditional load behaviour that is relied upon to help support system stability. It is thus ‘possible’ for EV chargers operating under this type of control to represent a significant share of system load, and in actively degrading system stability this would require ancillary services to manage – a ‘significant’ impact.

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[92] See ‘AC Service Limits’ in SAE J2894

Frequency disturbance risks

While better than constant power, EV chargers behaving as constant current type loads will not provide significant load relief in response to a frequency disturbance. Similar to a voltage disturbance scenario, this will degrade system stability and could require involuntary load shedding.

Table 8 identifies the key frequency disturbance risk identified through our research and consultations.

Risk 1.2.1 describes the challenge of maintaining system stability in the absence of load relief for a significant frequency disturbance. Local equipment testing showed that step and ramp changes in frequency did not have any significant impact on EV charger behaviour. While this is desirable in that it suggests load will ride-through manageable frequency disturbances, it is also not a helpful response for supply and demand balancing. This could require load shedding on the distribution network to manage.

In the situation where the power system is experiencing frequency excursions and load does not support a natural correction, then frequency control services will need to be procured – a 'significant' impact on the bulk power system. This is characterised as an under-frequency disturbance (-3 Hz) as this is more significant for the bulk power system – it is more difficult to switch on supply than it is to switch off supply. In the 2030-31 timeframe, it is considered 'possible' that this risk is realised at the transmission-scale due to EV charging.

Table 8 – Frequency disturbance risk

#	Cause	Effect	Risk assessment
1.2.1	EV chargers represent a significant proportion of system demand and do not provide load relief in response to a significant frequency disturbance (-3 Hz).	The power system becomes unstable resulting in the activation of involuntary load shedding to manage supply and demand imbalance.	Probability = Possible Severity = Significant **Risk = Medium**

System restart risks

NER clause 4.3.1 requires AEMO to *manage activities reasonably required to effectively prepare for and coordinate a response to a major supply disruption* […]. System restart is a process, for re-energising a power system after a transmission-scale an outage.

System Restart Ancillary Services (SRAS) are procured by AEMO from generators with the capability to start, or maintain service, without electricity being supplied from the grid.

It is a role of distribution networks to incrementally reconnect load to match the capacity of generation at a point in time and the start-up load of reconnecting network areas needs to be reasonably estimated by distribution networks to achieve this. Significant errors in restart load estimates can cause voltage and frequency disturbances and complicate and delay system restoration.

Distribution networks have methods for determining estimated restart load by reference to pre-outage load, accounting for loads that are unlikely to automatically restart and loads that may restart at a higher level. 'Cold load pickup' refers to loads, like water or space heating/cooling, that may restart at a higher level due the need to make up for lost operating time. EV charging has the potential to exhibit cold load pick up characteristics.

Table 9 identifies the key system restart risk related to increased EV charging identified through our research and consultations. The risks are generally associated with uncertainty in how EV charging, as a major load, with potentially complex characteristics, would respond to reconnection.[93] This uncertainty can

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[93] The complexity is closely associated with the multiple *control modes* that can apply to EV charging (See *Load control modes*, p.17).

be addressed through ongoing learning from re-energisations routinely performed by distribution areas after localised outages.

Risk 1.3.1 describes a situation where distribution networks are unable to accurately predict start-up loads, resulting in a delay to system restart. Load may also reconnect at material higher or lower levels than estimated causing voltage and frequency excursions and further delays the restoration process. The risk is considered 'rare' due to the historic rarity of power system restoration events. It is categorised as 'significant' as restoration load uncertainty may require AEMO to secure additional primary and secondary control as part of the restart procedure.

Table 9 – System restart risk (automation layer)

#	Cause	Effect	Risk assessment
1.3.1	EV chargers reconnect to distribution networks after an outage with substantially higher or lower load than estimated.	Restoration load variances create voltage and frequency disturbances during recovery and increased complexity materially delays system restoration.	Probability = Rare Severity = Significant **Risk = Low**

Application Layer risks

Application layer functionality, which is associated with higher-level communications and software, presents a different set of possible risks to the power system. When compared to automation layer responses, there is the potential to create upward load steps (rather than steps down in response to a disturbance) and these steps may be higher in magnitude, including switching from generation to load (if bidirectional). In some case, such load steps could be reasonability predicable (such as responding to a negative price event) or entirely unpredictable in the case of a cyber-attack.

Figure 17 illustrates one scenario where 33% of EV chargers step up their load simultaneously at peak time.

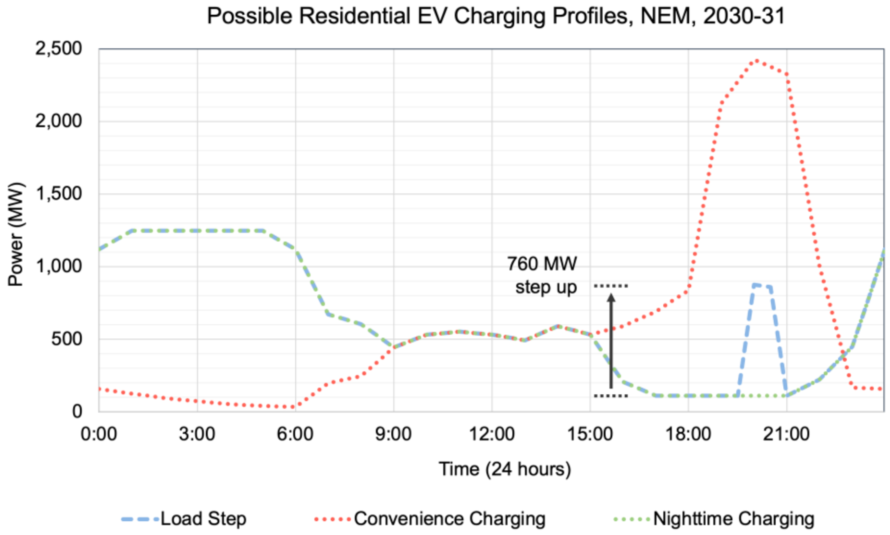

Figure 17 – Load step up as one third of charging EVs in the NEM respond counter to system needs.

In the established automotive electronics manufacturing industry, one supplier accounts for almost 20% of total market share.[94] Based on industry consultation, there are only a few suppliers of the underlying

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[94] IBISWorld (2023) *Robert Bosch GmbH - Company Profile*

charging equipment and technology for smart and bidirectional EV chargers. As such, it is conceivable that one supplier may represent a third of EV chargers in the field in the medium-term. The situation is similar for technology and service providers.

Cyber security risks

One scenario that may lead to a large load step is the compromise of a management system controlling a fleet of EV chargers by deliberate, malicious cyber-attack. With a high penetration of EVs, this could represent a load step at the scale of a large generating unit and may require involuntary load shedding to control.

Table 10 identifies the key cyber risk identified through our research and consultations.

Table 10 – Cyber security risks

#	Cause	Effect	Risk assessment
2.1.1	A CSMS is compromised by cyber-attack and a fleet of EV chargers behaves counter to system needs.	The power system experiences a very large load step up which causes widespread loss of power as involuntary load shedding activates.	Probability = Likely Severity = Severe **Risk = Very High**
2.1.2	OEM IT infrastructure is compromised by cyber-attack and used to push compromised firmware to an EV charger fleet.	The power system enters an insecure operating state as the control systems of a fraction of the national EV charger fleet are changed to respond counter to system needs.	Probability = Possible Severity = Significant **Risk = Medium**
2.1.3	Aggregator systems regulated under national cyber security provisions are compromised by a malicious actor and a fleet of EV chargers behaves counter to system needs.	The power system experiences a very large load step up resulting in involuntary load shedding.	Probability = Unlikely Severity = Severe **Risk = High**

Risk 2.1.1 highlights the cyber security threat for managed EV charging from what is perhaps the most obvious vector – through a Charge Station Management System (CSMS). In the medium-term, it is conceivable that there will be considerable market concentration for the back-end systems for EV smart charging, and hence the impact of this attack could be of a magnitude great enough to require involuntary load shedding.

Widespread loss of power while cyber responses are coordinated would be a ‘severe’ impact. Under present policy settings, this would probably not fall under industry-specific cyber security regulation, and the cyber security posture of industry is mixed. As such, it is considered ‘likely’ that this risk could be realised.

Risk 2.1.2 describes the risk associated with an alternative vector. In addition to Charge Point Operators, OEMs often also maintain a link to EV chargers to manage equipment, including to update firmware. This vector also has the potential to be exploited to compromise a fleet of EV chargers, and in particular to change automation layer settings for system security functions.

This could lead to an insecure operating state for the power system as the autonomous functions of EV chargers are modified to counter grid-friendly behaviour settings – a ‘significant’ impact, in that it would require the procurement of addition ancillary services to ensure a secure operating state (see discussion of disturbance risks). This is considered ‘possible’ – a lower probability than Risk 2.1.1 discussed above as the lower severity makes this a less attractive target for a malicious actor.

Risk 2.1.3 describes a similar risk to that associated with a CSMS, and in fact may ultimately flow through to EV chargers via the same system. In this case, however, the primary vector is aggregator systems operating a fleet of EV chargers for market participation. which could be compromised in a similar manner to CPO systems. This could have the same 'severe' impact; however, this is less likely to occur due to cyber security provisions under the Security of Critical Infrastructure Act 2018.[95] It is thus rated 'unlikely' however it is considered a 'high' risk.

Software management risks

There is the possibility of an OEM compromising EV charger control systems accidentally, which for a significantly sized fleet could have a material impact on the power system.

Table 11 identifies the key software management restart risk identified through our research and consultations.

Table 11 – Software management risk

#	Cause	Effect	Risk assessment
2.2.1	An Original Equipment Manufacturer (OEM) deploys a flawed EV charger software patch which results in system protection activation that requires operator intervention to reconnect.	The power system experiences a very large load step down which causes an over-voltage cascade and results in widespread loss of power as protection systems activate.	Probability = Possible Severity = Severe **Risk = Very High**

Risk 2.2.1 describes a risk of deploying a faulty software patch or update that causes EVSE to malfunction. This can be any update from CSMS to the protection devices that measure input and output electrical signals of the charger or improper tuning of the charger control system.

The malfunction of the EVSE can be catastrophic, anywhere between turning off/disconnection from the grid to blowing up the charger/OBC of the vehicle. The former is impactful on the BPS level because, if the EVSE of a specific OEM are abundant in the NEM, a faulty software patch can disconnect all the EVSEs in an instant causing significant load drop. This event leads to the series of effects identified in from *Risk 1.1.1* to *Risk 1.1.7.*

EVSEs disconnect as a result of faulty software patch and when a group of EVSEs drop on the network, the cause drop in load as a step. This results in over-voltages on the network, which can be detected by EVSEs on the same network, disconnecting as a result to protect themselves. These events cascade until power system level protection measures are deployed.

EVSE equipment relies on semiconductor devices that are sensitive to damage under overvoltage conditions, and therefore involve over-voltage system protection internally, as identified in *Risk 1.1.6*. This can require operator intervention to reset the EVSE to normal operating conditions.

An overvoltage cascade can have 'severe' effect on the power system which can trigger power system protection devices and FCAS services to arrest the effects of over voltages which could be severe and expensive.

This risk is 'possible' given the emphasis on software in the operation of EVSE. Control systems and operation of different electronics inside charger often communicate with software which need to be updated to account for cyber security risks, data management and charger control setting for example. The risk from such interactions can easily propagate to BPS level given the volume of the EVSEs involved.

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[95] Australian Government (2022) Security of Critical Infrastructure Act 2018

Communications risks

The loss of communications, such as an NBN outage, for a fleet of EV chargers under smart management represents a similar risk to that associated with a cyber-attack. In the absence of regulation to prescribe behaviour in this scenario, it is 'possible' that an EV charger fleet operating under a smart charging profile could revert to charge where it loses a remote management signal. This could lead to a very large load step at a time demand management is in place (i.e., evening peak) that exceeds the capacity of ancillary services to manage at the scale of the bulk power system – a 'severe' impact.

Table 12 identifies the key loss of communication risk identified through our research and consultations.

Table 12 – Loss of communications risk

#	Cause	Effect	Risk assessment
2.3.1	An internet connection issue (cellular or wired) results in the loss of communications for EVSE in a region and smart charging reverts to offline control mode(s).	The power system experiences a very large load step up which causes widespread loss of power as involuntary load shedding activates.	Probability = Possible Severity = Severe **Risk = Very High**

While widespread communications outages do not happen regularly, issues with major telecommunications service providers are also not 'rare', and account management issues could also cause an outage. Where a CPO or Aggregator is relying on cellular communications, for example, there may be a significant number of EV chargers linked to one telecommunications account via SIMs. **Risk 2.3.1** could thus be realised by an administrative error which results in all those devices being simultaneously disconnected from the internet.

Diversity destruction risks

NEM electricity wholesale markets are characterised by highly volatile prices, varying between -$1000 and $16,600/MWh in any 5-minute settlement period.[96] Price variability is intended to support the NEM's energy transition by driving investments in peaking generation and energy storage, as well as greater demand side participation. The AEMC's Reliability Panel's has recommended a progressive adjustment in the level of the NEM Market Price Cap to achieve an MPC of $21,500/MWh by July 2026.[97]

Emerging digital technologies and recent market reforms are creating greater scope for EV charging and other flexible loads to participate in wholesale electricity markets. This can occur directly (for customers on a spot passthrough retail tariff), or indirectly through aggregation services whereby BTM demand and generation is varied to manage an electricity retailer's wholesale market exposure.

These arrangements can be described as conforming to one of two different technology-agent models:

- **Utility agent model** – A retailer or network controls the customer's assets to manage their own price/risk exposure (sometimes compensating the customer for the right to control their assets). The DER is an agent of the utility.
- **Customer agent model** – The customer employs smart controls to manage their own risk/price exposure, including wholesale or retail electricity price exposures. The DER is an agent of the customer.

Both arrangements offer potential benefits to power system reliability and security and can contribute to greater renewables utilisation and lower electricity prices and emissions. As these models become more

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[96] AEMC (2023c) *Schedule of reliability settings - 2023-24 financial year*

[97] AEMC (2022) *2022 Review of Reliability Standards and Settings - Final Report*

prevalent, they can also be expected to contribute to greater demand variability, price-demand elasticity, and reduced demand diversity.

EV charging will be one of the most valuable flexible resources in Australia's energy transition. Having this flexibility located BTM does, however, create risks that need to be fully considered. For example, while AEMO will be able to observe demand elasticity changing over time, and account for this in demand forecasting, unlike scheduled resources, it currently has no way of limiting price responsive behaviour of BTM resources. This has implications for power systems security and the volume and cost of ancillary service procurements that manage forecasting error. **Table 13** identifies four risks associated with more coincident and price responsive behaviour, and more generally, the 'destruction' of demand side diversity.

Table 13 – Diversity destruction risks

#	Cause	Effect	Risk assessment
2.4.1	EV chargers switch on or off simultaneously in aggregate due to a change in ToU tariff band, dynamic prices signal, mandatory off-peak charging or direct load control.	The power system experiences a very large load step leading to an extreme RoCoF or frequency excursion that exceeds the capacity of voluntary frequency control schemes.	Probability = Likely Severity = Major **Risk = Very High**
2.4.2	EV chargers switch on and off repeatedly in response to (5 min) changes in dynamic pricing in the National Electricity Market (NEM).	The power system experiences oscillatory closed-loop price-demand interactions which impacts system stability and market behaviours.	Probability = Likely Severity =Significant **Risk = High**
2.4.3	EV chargers switch on and off repeatedly in response to changes in dynamic operating envelopes (DOE) which inadequately account for behaviour of EV chargers.	The power system experiences slow and moderate magnitude oscillatory behaviour from EV chargers on a distribution network.	Probability = Possible Severity = Minor **Risk = Medium**
2.4.4	EV chargers switch on in aggregate in preparation for an emergency alert (e.g., severe weather forecast) or potential supply shortfall (e.g., Lack of Reserve notice).	The power system experiences unconstrained ramping which strains regulation and contingency FCAS reserves.	Probability = Possible Severity = Significant **Risk = High**

Risk 2.4.1 relates to a step up in EV charging load within a trading interval that (without further mitigation) causes a drop in frequency that exceeds the capacity of primary and secondary frequency schemes triggering UFLS.

This risk is rated as 'likely' by 2030 (and beyond that it could become 'almost certain'). The high likelihood is influenced by separate modelling conducted by enX[98] and ARENA trials, which indicate that there are significant financial benefits for vehicle owners in having price responsive charging profiles. This includes smart and bidirectional charging under a time-of-use (ToU) or spot passthrough retail tariff. Were many consumers to obtain this financial benefit, this risk would likely materialise.

The severity of this risk is considered 'major' based on an expectation that load increases within a trading interval (for example, responding to a negative spot price) could result in UFLS. As a point of reference 1% of EV chargers turning on across all NEM regions in 2030, equates to 220MW. By 2040, a proportionally sized load step up would equate to around 870MW.

A way to mitigate this risk is by ensuring AEMO's demand forecasting models account for growing demand elasticity (to reduce demand forecasting error) and where appropriate, encouraging a greater share of

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[98] enX (2023) *Opportunities and Challenges for Bidirectional Charger in Australia*

flexible load into central dispatch. Ramp rate requirements and randomised delays for EVSE should also be considered.

While imposing ramp rates or randomised delays on EV chargers would mitigate frequency impacts of load step changes, the ramp length would need to be punitive (e.g., 5 minutes) to fully mitigate coincident stepping of BTM loads. In effect, if not integrated effectively into market, portfolio and product design ramp rate requirements could inhibit spot market participation by relevant loads which would run counter to the need to encourage greater demand side participation. Slow ramps and staggered starts can also impact consumer experience and costs for EV charging.

Risk 2.4.2 can be considered a potential secondary effect of risk 2.4.1 that is limited to BTM resources that are exposed to wholesale prices (under either *utility agent* or *customer agent* model).

Specifically, this risk sees a 'closed-loop price-demand interaction' occur, where, for example, low prices lead to increased load, which lead to high prices, which leads to decreased load, which leads to low prices (and so on). Such affects have been demonstrated in power system simulations such as the Callaway and Hiskens' (2011) [99] study (described at page 37). The probability and severity of such oscillations is largely dependent on the volume of spot-exposed demand, the sensitivity of the generator merit order to load changes, and AEMO's ability to measure and account for demand elasticity prior to dispatch.

The probability of this occurring is considered 'likely' by 2030. The severity of the impact is considered 'minor' meaning it is able be managed with the scope of regulation and contingency FCAS requirements. The effect is likely to be more pronounced during periods of supply scarcity (where the price is more sensitive to load changes) and as more BTM EVs charging becomes exposed to wholesale market risk beyond 2030.

As with the previous risk, a way to mitigate this risk is by ensuring AEMO's demand forecasting models account for growing demand elasticity (to reduce demand forecasting error) and, where appropriate, encourage a greater share of flexible load into central dispatch.

Risk 2.4.3 is an extension to the previous risk, however rather than demand and price working in a closed feedback loop, the interaction is between demand and local area dynamic import or export limits, or other methods of load control.[100]

In the case dynamic limits, high demand could lead to tight load limits, leading to reduced demand, lower load limits, leading to high demand (and so on). While this risk considered 'possible', it appears to have a low probability of escalation under dynamic limits due to the inherent ability of distribution networks to dampen the oscillation by calibrating the load (or export) to limit the oscillation.

Should this occur in a large distribution area, the expert reference group considered this could have a minor, but observable impact on the transmission power flows and frequency, within the parameters of normal operation. Unlike risks 2.4.1 and 2.4.2 where AEMO does not have the ability to directly dampen oscillatory behaviours of BTM resources, DNSP are able to mitigate the oscillatory behaviour by setting of export or load limits.

Overall, the risk is rated as 'medium', meaning that mitigation (by NSPs) is desirable. The most relevant mitigation strategy for networks is to develop models that appropriately account for constraint-demand elasticity in the allocation of hosting capacity, and this can be refined over time. We do not envisage this being a material risk to broader power system operation unless dynamic limits are poorly executed by NSPs.

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[99] Callaway and Hiskens (2011) *Achieving Controllability of Electric Loads*

[100] Dynamic import or export limits are *largely* intended to represent the physical hosting capacity of a distribution network (subject to voltage and thermal constraints) or to achieve transmission scale minimum system load outcomes. However, SAPN has proposed a trial whereby export limits could also reflect wholesale market conditions (see *SA Power Networks Market Active Solar Trial*).

Risk 2.4.4 relates to a situation whereby EVs commence or accelerate charging due to an expectation of a future loss of power supply. This could be associated with the need to have a specific SoC at a point in time for transport purposes, or to sure-up back-up power supplies for a possible grid outage.

This is akin to customer refuelling their cars before a major storm. Smart charging and V2H/B management software could include programs to monitor a range of forecasts and alerts as an input to charge control and scheduling. Unlike ICE vehicles, preparatory charging behaviour is not mitigated consumer awareness or action – it could be fully automated. While the event alert may be localised, where enough EV chargers respond to the same input simultaneously, this could impact the bulk power system. For example, a 10% of vehicles in Queensland commencing charging at 7.4 kW would result in a load step of around 550 MW in 2030.

This probability of this occurring is considered ‘possible’ in the 2030s and the impact is considered ‘significant’, If unmanaged, a large and unexpected load increase could impact power system frequency. In the near term, it is considered this issue can be managed by AEMO proactively monitoring the evolution of event-based charging behaviour over time and, if necessary, accounting for potential coincident load responses in load forecasting models and ancillary service procurements. In the longer term, industry should explore opportunities to bring more charging into a scheduling framework, and imposing ramp rate limitations on high-capacity charging infrastructure.

8. INSIGHTS AND RECOMMENDATIONS FOR THE NEM

The aim of this report is to define and prioritise risks that may be associated with charging Australia's growing EV fleet. Based on consultation with local and international experts, this report has characterised the power system risks associated with EV charging into six groups:

1. Voltage disturbance risks
2. Frequency disturbance risk
3. System restart risks
4. Cyber security risks
5. Software management risk
6. Loss of communications risk

The research, analysis and consultation undertaken in this study explored the origins and potential impacts of these risks with reference to technical standards for EV chargers and other considerations. This necessitated an examination of the broader context of the changing nature of loads, in particular a trend towards converter-based equipment such as air conditioners. In turn, this informed an assessment of the relative priority of risks associated with EV charging for the bulk power system in the medium term.

It is important to note that a strict focus on EV charging impacts at the transmission-scale in the NEM over the 2030 timeframe has limitations that are acknowledged in this assessment. For example, while EV charging is unlikely to be a primary cause of voltage collapse in 2030, it could exacerbate existing challenges that are material for network operation. Similarly, mitigation action focused narrowly on the Australian/NEM context would miss critical opportunities to address potential future challenges early, before reactive interventions are required.

Potential pathways for risk mitigation are thus described below with a view to broader trends and initiatives, locally and internationally, which discussed in more detail throughout the body of the report.

Mitigating disturbance ride-through risks

Like other electronic loads, an EV charger's ability to withstand voltage and frequency disturbances is not inherent, it needs to be programmed into EVSE firmware.

EV charging loads have the theoretical potential to provide grid support services including frequency response and synthetic inertia, however these are yet to be fully demonstrated in the CCS technology stack and limitations are likely to exist with regard to communication latencies between grid monitoring hardware, where the local network state estimation generally occurs, and the in-vehicle battery management system which ultimately govern the physical response of the battery.

The capability of EVSE to withstand disturbances and provide grid support services needs to be considered at the product level and explored through equipment testing and international collaboration on new standards development.

DNSPs may be best placed to observe voltage ride-through characteristics of EVSE during early stages of EV uptake. In some cases, they will also be more exposed to the risks of EV load drops resulting from voltage sags as initially, these effects may be concentrated on specific feeders and distribution zones. There is an opportunity for AEMO to collaborate with distribution businesses in ongoing monitoring and knowledge sharing to inform NEM-wide strategies, before risks become material at a transmission-level. The extension of the DER Register to EVSE, as recommended by the ESB, will increase the potential scope of locational analysis and the performance characteristics of different products.

Given the dynamic state of product and standards development in the eMobility sector, further authoritative testing of equipment should continue to better understand the risks in power system contexts. This includes the interplay of unidirectional load with embedded generating units, as well as smart charging and energy management systems. Dynamic management with communications, and bidirectional charging capabilities, will support EV integration and should be encouraged. This will, however, introduces additional risk to be managed in the broader smart grid environment.

Australia sits at the end of international supply chains for both the manufacture of the core power electronics that determine the disturbance ride-through characteristics of EVs and EVSE. Disturbance ride-through concerns for EV charging are not unique to Australia, with early-stage risk analysis occurring in the UK and North America (discussed in Chapter 4). Our analysis indicates that there is time for Australia to leverage this work so that we can adopt internationally aligned processes and standards. This will reduce the risk of Australia applying unique standards for products that limit local equipment supplies, increasing costs and limiting choice for Australian consumers.

Specifically, there is scope, and time for Australia to engage with the IEC *Systems Committee for Smart Energy,* which is currently developing the Systems Reference Deliverable IEC 63460,[101] *Architecture and use-cases for EVs to provide grid support functions*. Similarly, a revision to SAE J2894/1 is under development, as are efforts to address an identified gap concerning ride-through requirements for V2G EVSE by the IEEE and UL Solutions (formerly known as Underwriters Laboratories).

The majority of EV charging in the NEM (including bidirectional charging) is expected to be DC, meaning that key power conversion and electrical control systems will reside in a charger external to the vehicle. The most prospective regulatory pathway to the imposition of minimum grid performance product standards in the Commonwealth GEMs Act (2012). As described in Chapter 0, the GEMS legislation is currently subject to review and legislation changes may be required to extend its coverage to EVSE.

Ideally, internationally aligned minimum requirements would apply to all forms of charging including where power conversion occurs within the vehicle.

Recommendation 1: AEMO should work with Standards Australia to establish formal engagement with ANSI and IEC to coordinate international efforts to establish disturbance ride-through and other inherent device response settings for EV chargers and other major electronic loads.

Recommendation 2: As part of its international engagement, industry should collaborate on the development of requirements for constant current operation and active power frequency response for EV charging and other major electronic loads. These requirements should be informed by local and international power system studies that explore the impact of large-scale EV charging on voltage collapse and angle instability and consider the potential interaction of the generation and load during disturbances.

Recommendation 3: AEMO should work towards incorporating disturbance ride-through requirements for EV chargers and other major electronic equipment in the form of internationally aligned and nationally consistent minimum product standards. AEMO should work with DCCEEW to ensure that planned reforms to the *GEMS Act 2012* consider its extension to power system security requirements that support Australia’s emission-reduction objectives.

Mitigating cyber security and software management risks

Australia’s uptake of electric vehicle presents new challenges to power system planning and operation. While EV charging shares many characteristics with other electronic loads, it generally has a greater potential for to be orchestrated at scale, and flex in response to price or other remote signals. Dynamic management with communications for smart charging is essential for effective EV integration, however this introduces additional risks to be managed, including the risk of a cyber-attack.

The threat vectors are not limited to Charge Station Management Systems reliant on open standards-based communications protocols, and issues are not limited to technical settings. A cyber-attack could exploit the link OEMs may have with their equipment for the purposes of maintaining and upgrading firmware, or aggregator systems used to manage a range of distributed energy resources for market

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[101] IEC (2022) *Architecture and use-cases for EVs to provide grid support functions*

participation. Some of these applications may utilise proprietary protocols and rely on internal policies for cyber security governance.

Recommendation 4: AEMO continue efforts to support a holistic consideration of cyber security and software management-related risks for all forms of DER, including security of communications and broader institutional governance and controls for relevant industry participants.

Mitigating loss of communications and system restart risks

Demand management, or demand-side participation, is desirable or perhaps even essential for the efficient utilisation of system assets and the effective balancing of supply and demand for system operation. The downside of a reliance on these mechanisms is the risks that arise where they are inoperable or overridden, for example during or after a communications or power outage. It is therefore important that these scenarios are considered when developing technical requirements.

Recommendation 5: Industry should collaborate to establish a program to monitor and share data on localised load responses to a loss of communications and reenergisation after a network outage. This information can inform a more detailed assessment of potential future transmission-scale risks including implications for system restart procedures.

Recommendation 6: As part of its engagement with international standards processes, AEMO should collaborate with network businesses to define desired start-up and offline behaviour requirements for EV chargers and other major electronic loads including data centres.

Mitigating load step risks

By the early 2030's the NEM's EV battery fleet will represent the largest, and one of the lowest cost energy storage resources to support our energy transition.[102] While EV charging flexibility offers inherent value, unconstrained operation can result in substantial coincident load steps, resulting in system security impacts at all levels of the power system.

Coincident load steps will be first observed locally in distribution network areas with high EV penetrations. There is an opportunity for AEMO to work with distribution network businesses to understand the coincident behaviour of EVs at the local level, before transmission risks become material. It is important that product standards are internationally aligned are prioritised and that flexibility is maintained for consumers and industry to actively participate in (and capture value from) energy markets.

Recommendation 7: Network businesses should implement an ongoing monitoring program to assess the impact of weather event forecasts and market notices on load changes (e.g., pre-charging of EVs ahead of a storm or price spike) or forecast Lack of Reserve. Monitoring data can be used to assess changes in charging behaviour to inform AEMO load models (minimising load forecasting error) and FCAS procurement.

Recommendation 8: Industry should work with international standards organisations to establish nationally aligned ramp rate and/or randomised delay requirements for EV charging and other flexible loads, balancing system security risk with the need to encourage dynamic demand-side participation.

Recommendation 9: AEMO and industry should consider how market reforms, including the Integrating Energy Storage and the Scheduled Lite Rule Changes, could be designed and implemented to enable a greater share of EVs participating in central dispatch.

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[102] enX (2023) *Opportunities and Challenges for Bidirectional Charger in Australia*