INSIGHTS FROM ZERO EMISSION BUSSES (ZEB) ADVISORIES





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Abstract

Zero Emission Buses (ZEBs) are redefining public transport by dramatically reducing emissions and ushering in cleaner, more efficient mobility systems. This paper synthesises insights from three key advisories issued by the Bus Industry Confederation (BIC), offering a critical examination of existing regulatory frameworks, operational barriers, and emerging trends in ZEB deployment. In addition to discussing industry best practices—spanning battery management, hydrogen safety, and infrastructure design—the advisories are situated within a broader international context. Building on these findings, the paper presents a practical implementation framework and a decision-support tool for transitioning to ZEB operations. It concludes with targeted recommendations to enhance safety protocols, strengthen standardisation, and improve overall system integration for sustainable and scalable ZEB adoption.

Keywords: Zero-Emission Buses (ZEBs), Battery Electric Buses (BEBs), Fuel Cell Electric Vehicles (FCEVs), Rechargeable Electrical Storage System (RESS), Compressed Hydrogen Storage System (CHSS), Charging Infrastructure, Hydrogen Safety, Policy Development, Regulatory Frameworks, Safety Protocols

1. Introduction

Transitioning to Zero Emission Buses (ZEBs) is not just a matter of meeting local regulatory requirements or complying with international standards; rather, it is part of a global shift toward sustainable transportation and decarbonized energy systems. As cities worldwide contend with poor air quality and congestion, governmental bodies and transport agencies are looking to zero-emission fleets to reduce greenhouse gas (GHG) emissions, improve public health, and enhance the overall quality of urban life.

The Bus Industry Confederation (BIC) Zero Emission Bus Advisories [1][2][3] demonstrate Australia's proactive approach by offering a structured framework to guide operators, manufacturers, and government bodies through key considerations like electric powertrain design, ZEB maintenance and operation practices, as well as fixed infrastructure requirements. This aligns with international trends in heavy vehicle electrification where bus operators are rapidly electrifying fleets to meet policy mandates and societal expectations regarding cleaner air and lower carbon emissions.

However, as the Advisories underscore, the success of ZEB deployment hinges on collaboration across multiple stakeholders, from the utility sector and grid operators—ensuring sufficient electricity supply and reliability—to vocational training institutes that equip the workforce with the skills to maintain and operate these vehicles. In addition, aligning Australian Design Rules (e.g., ADR 109/00 and ADR 110/00) with global standards (UNECE regulations, FMVSS requirements, ISO guidelines) ensures that Australian bus fleets remain interoperable with emerging international best practices.

These considerations illustrate the broader socio-technical ecosystem required to make ZEBs viable. ZEBs must not only fulfill zero-tailpipe-emission requirements in principle, but they also need to integrate seamlessly into existing transit networks, depot infrastructure, and workforce operations if they are to become both cost-effective and reliable on a large scale.

2. Overview

The advisories present a substantial body of knowledge for the deployment and support of ZEBs in Australia, spanning regulatory guidance, technical standards, and real-world operational recommendations. Key takeaways include:

- **Regulatory Alignment**: ADR 109/00 & 110/00 with UNECE R100, R134, FMVSS No. 305, UN GTR No. 13 & 20) [4][5].
- **Safety Fundamentals**: ZEBs present different risks compared to conventional buses. The advisories integrate safety principles covering high-voltage electrical systems, high-pressure hydrogen tanks, and robust emergency response planning [1][2].
- **Infrastructure Complexity**: Transitioning to ZEBs requires careful coordination with grid operators, especially given the Australian grid's vulnerability to extreme weather events. Advisory 3 details strategies for depot design, backup power systems, and future microgrid integration addresses these challenges [3].
- **Operations and Maintenance**: ZEBs require specialized service protocols and workforce skills. Standardized training frameworks—like those offered by TAFE and RTOs—ensure technicians understand best practices for managing battery systems, hydrogen equipment, and high-voltage components [2][8].

- **Evolving Technologies**: Rapid innovations in battery chemistry (e.g., LFP vs. lithium-ion variants), hydrogen storage (350 vs. 700 bar), and power electronics mean that operators must remain vigilant in updating both infrastructure and vehicle procurement strategies.

Advisory 1 was developed to support the forthcoming Australian Design Rules 109/00 and 110/00 on zero emissions [4] [5]. ADR 109/00 is Australia's implementation of UNECE R100 under the 1958 agreement and lists UNECE R100, FMVSS No. 305 (49 CFR 571) and UNGTR No. 20 – Electric Vehicle Safety (EVS) as alternative standards [4]. Likewise, ADR 110/00 lists UNECE R134 – Safety related performance of HFCV and UNGTR No. 13 – Hydrogen Fuel Cell Vehicles (HFCV) as acceptable alternative standards [5]. The BIC recommends that the UN Regulations adopted by the European Commission and undergoing regular review by Working Party 29 continue to provide a substantive basis to support the Australian ZEV regulatory framework [1].

Advisory 2 recommends standards, regulations and best practices relating to the operation and maintenance of heavy vehicles with electric power train systems such as diesel electric hybrid, battery electric or fuel cell electric. It is designed to provide a guidance on: What to be aware of in relation to ZEB operations and maintenance, and where to look for further information.

Advisory 3 addresses the integration of ZEVs into existing power grids, anticipates power supply disruptions, and outlines best practices for infrastructure setup and maintenance. The Advisory aims to bolster the adoption of ZEVs by ensuring reliable, safe, and efficient infrastructure to help facilitate Australia's transition towards sustainable transportation.

3. Voltage Standards

The advisories refer to the automotive voltage classes for high voltage (HV) and low voltage (LV) per ISO 6469-3:2018 [6]. Care must be taken to not confuse these voltage classes defined with AS/NZS 3000:2018 Australian Wiring Rules [7]. In automotive applications, LV systems are defined as those operating at or below 60 volts direct current (DC) or 30 volts alternating current (AC), covering traditional vehicle electronics like starter motors and lighting. In contrast general electrical standards categorise LV as below 1,000 V AC. or 1,500 V DC., with HV defined as anything above these thresholds, extending to thousands of volts (e.g., 10 kV to 500 kV or higher) for applications in power transmission and industrial processes.

4. Workplace Safety, Risks and Controls

The Advisories are based on the Safety Principles which are designed to cover the key aspects of operational safety in the context of ZEBs, including: Harmonization and Consistency in Safety Practices, Compliance with Safety Standards and Guidelines, Qualified and Trained Personnel, Use of Electrically Safe Equipment, Risk Management and Minimization, Regular Safety Audits and Inspections, Emergency Preparedness and Response, Safe Handling of Batteries and Fuels and Proactive Maintenance Schedules.
ZEBs present different risks compared to conventional vehicles due to the higher voltage of electrical systems and high-pressure hydrogen systems. Some key high-level risks to be aware of are outlined in Figure 1.

5. ZEB Fundamentals

Zero Emission Buses (ZEBs) differ fundamentally from ICE buses, particularly in their reliance on advanced energy systems. There are mainly two types of ZEBs currently in the market: Battery-Electric Buses (BEBs), and Fuel Cell Electric Vehicle (FCEVs). BEBs utilise Rechargeable Electric Energy Storage Systems (REESS), which consist of high-capacity lithium-ion or lithium iron phosphate batteries. Fuel Cell Electric Buses (FCEVs) employ Compressed Hydrogen Storage Systems (CHSS), integrating high-pressure hydrogen storage and fuel cells to generate electricity on demand.

Risk Category	Potential Impact and Specific Risks	Mitigation Strategies	Risk Level	Responsible Party	Review Frequency	Standards / Guidelines
High Voltage Electrical System	Fire, Electric Shocks, Arc Flashes	Regular inspections, safe practices, PPE, maintenance, training	High	Maintenance Team	Annually	AS/NZS 5139, NFPA 70E
RESS	Explosion, Toxic Gases, Exposure to Electrolytes	Battery protocols, PPE, thermal management, emergency procedures, training	High	Safety Officer	Bi-annually	ADR 109/., AS ISO 19880-1, NFPA 2
Untrained Technicians and Personnel	Errors leading to accidents or system damage	Comprehensive training programs, certifications, continuous education	High	HR and Training Departments	Annually	AS/NZS 3000, AS/NZS 45001
Thermal and Fire	Thermal Burns, Fires from Short Circuits, Overheating	Emergency plans, protection equipment, fire systems, safe handling	High	Fire Safety Manager	Annually	AS 2359.1, ISO 3691-1
EV Charging Infrastructure	Electrical hazards, Overloading, Faulty installations	Regular inspections, adherence to installation standards, training on safe operation and emergency response	Medium	Facilities Management	Annually	AS/NZS 3000, AS/NZS 5139
Maintenance Operations	Tool Misuse, Inadequate Training, Lack of Safety Protocols	Training, skill development, safety protocols, calibration	Medium	Training Department	Annually	AS 3745, NFPA 70E
Emergency Response Training	Unprepared for EV-specific emergencies	Specific scenario training, drills, emergency plans	Medium	Emergency Response Team	Annually	AS/NZS 14001, EPA Guidelines
Cybersecurity Risks	Unauthorized access, hacking	Security protocols, cybersecurity training, system updates	Medium	IT Security Team	Bi-annually	AS/NZS 1715, NIOSH Guidelines
Hydrogen Fuel	Gas Leaks, Pressure Risks	PPE, chemical handling, ventilation, refuelling procedures, training	Medium	Operations Team	Annually	AS 1670, ISO 26262
Transportation and Handling	Heavy Lifts	Warning labels, handling equipment, special tools, and procedures	Low	Logistics Manager	Bi-annually	AS 1657, ANSI A1264.2-2012
Tripping Hazards	Tripping from Cables and Equipment	Signage, cable management, overhead systems	Low	Facilities Manager	Annually	AS/NZS 3000, ISO 31000
Environmental Risks	Spills, Leaks affecting environment	Containment, spill kits, environmental protection training	Low	Environmental Officer	Annually	AS ISO/IEC 27001, NIST Cybersecurity Framework
Health Monitoring	Exposure to hazardous substances	Health checks, exposure monitoring, medical training	Low	Health and Safety Officer	Annually	AS/NZS 1269, ISO 9612
Static Electricity	Ignition of flammable gases	Grounding, static dissipative tools, training	Medium	Maintenance Team	Annually	Local Safety Regulations, AS 1319
Public Safety	Risks to bystanders during operations	Public safety training, barriers, signage	Low	Public Relations	As needed	AS/NZS 5139, NFPA 70E

Figure 1. ZEB Operational and maintenance risks

BEVs feature battery packs for power storage, linked via junction boxes for electrical current distribution. An electric motor drive converts the DC from the batteries to AC, powering the motors that drive the wheels and regulate motion. Auxiliary systems like HVAC and air compressors, running off the same batteries, function independently to not affect propulsion. The charger socket/s or Pantograph connects the bus to the power grid for recharging, readying it for continuous operation.

The FCEV system architecture for Zero Emission Buses includes a hydrogen supply that feeds a fuel cell system, converting hydrogen to electricity, managed by an Electric Control Unit (ECU). The current is regulated via a DC/DC voltage converter and either stored in a power battery or supplied directly to an electric motor. A Vehicle Management Unit (VMU) oversees energy distribution, while an integrated controller and Motor Control Unit (MCU) manage the motor. The electric motor drives the wheels through a differential, and a radiator maintains the fuel cell system’s optimal temperature.

6. Electric Vehicle Safety

ISO 6469-2 2022 outlines safety requirements for electric road vehicles, focusing on operational safety to protect occupants and bystanders. It covers driving modes, RESS power levels, reverse driving, external sound generation, parking, connection to external circuits, and information for first responders. ISO 6469-3 2022 includes safety requirements for High Voltage (officially called voltage class B) circuits of electric propulsion systems.
The High Voltage Interlock Loop (HVIL) is a safety system in Zero Emission Buses (ZEBs) that monitors the integrity of the high voltage (voltage class B) electrical system cables and connections. It detects disconnections and cable faults and automatically shuts down the system to prevent electric shock. The High Voltage Interlock Loop (HVIL) system in Zero Emission Buses (ZEBs) might activate in scenarios such as a collision or maintenance error.

7. Hydrogen Safety

Hydrogen fuel is extremely flammable and should be considered in a similar manner to other flammable fuels such as natural gas or petrol. To safely maintain or operate a hydrogen system the flammability and explosiveness of the gas must be considered.

Three elements of combustion: combustion supporting substance, combustible substance and flash point (ignition source). In terms of hydrogen safety, personnel should focus on avoiding contact with combustion supporting substances or flash point (ignition source). Hydrogen fuel systems in Zero Emission Buses (ZEBs) operate under high pressure, generally up to 350 bar. This is relatively low compared to the 700 bar proposed for trucks. Key elements of high pressure safety include system integrity, pressure relief mechanisms and lead detection and monitoring.

The hydrogen fuel system typically consists of several critical safety and functional components designed to handle the safe delivery, of hydrogen gas to the fuel cell (sometimes referred to as a fuel cell stack). These components include a hydrogen filling port to add fuel to the CHSS, check valves, limiting valve/s, hydrogen cylinder/s, high-pressure gas storage unit, tail plugs, pressure and temperature transducers for monitoring, safety valves (unloading valve) to automatically release pressure when too high for circuit safety, cylinder top valves, pressure relief valves and filters, see Figure 2.

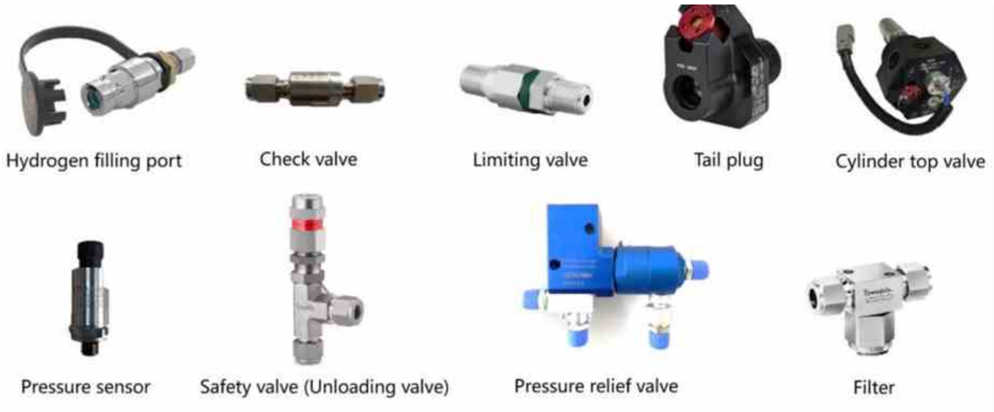

Figure 2. Hydrogen System Components

8. Post Crash Safety

ISO 6469-4 2015 outlines post-crash electrical safety requirements for High Voltage (Voltage class B) electrically propelled road vehicles. ISO 23273 and related standards provide guidelines for managing risks associated with hydrogen fuel systems post-crash. These standards focus on preventing hydrogen leaks, fires, and ensuring the safety of passengers, first responders, and the public.

9. Electric Vehicle Maintenance and Repair

Australian Standard 5732:2022 Electric vehicle operations — Maintenance and repair [7] forms the basis of the advisories guidance for technicians working on ZEBs. AS 5732:2022 specifies requirements and guidance on the safe and appropriate handling procedures for those within the mechanical repair, body repair and refinishing industries when working on plug-in electric vehicles (PEVs), hybrid electric vehicles (HEVs), battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell electric vehicles (FCEVs). AS5732:2022 sections include safe work practices, general service working areas, service and repair procedures for ZEBs, damaged high voltage batteries, fire safety and decommissioning, re-use, and recycling of ZEBs.

Advisory 2 expands the guidance to include checklists for REESS maintenance, handling and storage, routine vehicle care and hydrogen systems. ZEB specific tools and equipment are required which include general Protective Personal Equipment (PPE), PPE for working on energised components, exclusion barriers, insulated tools, digital multi-meter with Cat III 1000- volt rating, insulation testers, scan tools and oscilloscopes, safety insulated step ladders, lifting tables for battery packs, rescue kits for high voltage work, including rescue hook, and specialised first aid emergency kits.

10. Training and Licensing Requirements

Automotive training and licensing in Australia are structured processes that ensures individuals are adequately skilled and knowledgeable about vehicle mechanics, safety, and regulations. Vocational Training is largely harmonised under the Australian Qualifications Framework (AQF) and provides the certificate courses and skill sets that cater to the demand for skills in electric vehicle (EV) technology, hydrogen handling, and EV charging infrastructure. Currently for automotive technicians the training can be divided into two areas: Apprentice and qualified technician upskilling.

Automotive technicians (Apprentices) are required to complete certificate courses offered by Technical and Further Education (TAFE) institutes or registered training organisations (RTOs). Currently, these courses range from Certificate II to Certificate IV levels in automotive technology and have the following specialisations as listed on the training.gov.au. AUR32721 - Certificate III in Automotive Electric Vehicle Technology is available for technicians wishing to specialise in the repair of electric vehicles and has both light and heavy vehicle specialisations, like existing Certificates III in Automotive Mechanical Technology. This qualification aligns with Australian Standards (AS) 5732 for Electric vehicle operations - Maintenance and repair. It includes 16 core units and 13 elective units, with specializations available for light and heavy vehicles. This qualification, first released in February 2022, is part of the Automotive Retail, Service and Repair Training Package.

Skill sets are designed to upskill qualified heavy vehicle mechanic, light vehicle mechanics and automotive electricians with the units of competency for maintaining ZEBs. BIC identified potential gaps in skill sets for upskilling heavy vehicle technicians, including *AURETK002 - Use and maintain electrical test equipment in an automotive workplace and AURETH103 - Diagnose, remove, and replace heavy electric vehicle RESS.* BIC also identified non-technical hydrogen and micro-credential course information for operators and suppliers. Including Certificate II in driving operations, Certificate IV in supply chain operations. Recently, new skill sets which form the basis of a hydrogen safety certification have been developed including Basic hydrogen safety, monitor and control hydrogen gas distribution networks, and fault find and repair hydrogen storage equipment.

In most Australian states, automotive mechanics need to obtain a motor vehicle repairer's licence. The requirements for this license vary by state but generally include a combination of education, experience, and sometimes a criminal background check.

11. Emergency Response

One invaluable tool for enhancing the safety and efficiency of emergency responses is the ANCAP (Australasian New Car Assessment Program) Rescue App. The ANCAP Rescue App provides detailed diagrams and information sheets directly from manufacturers, outlining the location and nature of key vehicle systems, including high-voltage cables, battery units, and hydrogen tanks, see Figure 3.

Collaboration between local emergency services, vehicle manufacturers, and ZEB operators can facilitate the sharing of critical information and best practices, ensuring a coordinated response to incidents. It is suggested Emergency services be engaged in pre-incident planning (updating emergency response/indicant plans) that considers the specific challenges posed by ZEBs, including potential scenarios in tunnels, depots, and public roads.

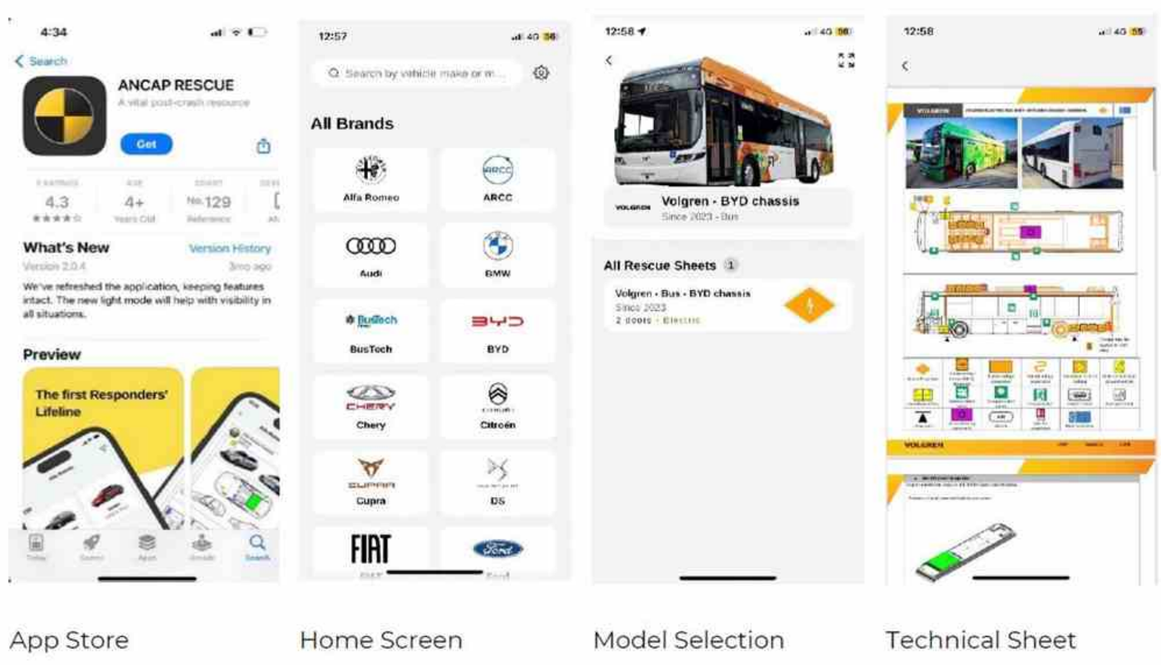

Figure 3. ANCAP Safety App

12. Energy Supply

The Australian power grid is a large and complex network designed for electricity demand across the continent. This grid encompasses the National Electricity Market (NEM) that connects five major regions along the east coast, and standalone systems in Western Australia and the Northern Territory, each with their unique structure and energy mix. The grid's operations are overseen by various operators and regulatory bodies, including the Australian Energy Market Operator (AEMO), which ensures electricity supply meets demand in real-time. The Australian Energy Market Commission (AEMC) plays a pivotal role in setting rules and policies to govern the market's functioning by the Australian Energy Regulator (AER).

Designing charging stations for BEBs and FCEBs within the NEM or SWIS requires careful consideration of location, energy pricing, renewable integration, and regulatory compliance to ensure efficient and sustainable operations. Operators must ensure that infrastructure complies with energy regulations and standards for seamless integration into the national grid and to secure any available incentives or subsidies. Proximity to transmission infrastructure can influence the feasibility and cost-effectiveness of deploying charging stations, especially for high-capacity, fast-charging.

Variations in electricity prices across different regions and times of day can impact the operating costs of charging stations. Designing infrastructure with Energy Storage Systems (ESS) or considering off-peak charging can optimise costs. ZEB operators must consider electrical engineering design, charger location, complexity of electrical assets, integration expertise, grid outages, grid connections/embedded generation applications, turnkey vs. multiple experts, outsourcing, proximity to transmission infrastructure, distribution infrastructure, trading into the NEM, flooding, development approvals and fire protection. Australia's electricity grid faces significant challenges, particularly from extreme weather events such as heatwaves and storms, which have historically impacted the reliability and security of the power supply. The AEMO has highlighted these weather events as major risks to the stability of the electricity system, emphasising the vulnerability of traditional, centralised power generation and the long-distance transmission infrastructure to such disturbances. The transition towards a more distributed system, with smaller, geographically dispersed units relying on a variety of renewable sources, is seen as a solution to increase the grid's resilience against extreme weather.

Advisory 3 provides information on backup power solutions for ZEB charging infrastructure and compares various technologies including: diesel generators, Battery Energy Storage Systems (BESS), Solar Photo Voltaic (PV) with storage, natural gas generators, fuel cell systems and hybrid systems.

In Australia, the interest in microgrids has surged, particularly in remote and rural areas where connection to the main grid is challenging or cost prohibitive. Microgrids not only offer a solution to energy access in these areas but also present an opportunity for communities to become more energy independent and environmentally conscious.

13. EV Charging Stations

This section focused on EV charging stations outlines various charging technologies and Total Cost of Ownership (TCO) considerations. It recommends ensuing vehicles and Electric Vehicle Supply Equipment (EVSE) comply with key international standards to ensure safety, reliability and interoperability.

CCS2 is the predominant standard in Australia, which supports both AC and DC charging. It is widely adopted across Europe and aligns with international standards, particularly those defined by **IEC 62196-2** (for AC) and **IEC** EV **62196-3** (for DC). In Australia, **CCS2** is not mandated by law but is the preferred standard due to its compatibility with both AC and DC charging systems. It consists of a nine-pin input that splits into two sections.

Pantograph systems are high-power charging solutions often used in Bus Rapid Transit (BRT) systems or at depots. These systems can be deployed either as "bus-up" (where the pantograph is attached to the bus) or "bus-down" (where the pantograph is on the infrastructure). They are particularly useful for where the bus quickly recharges at strategic points along the route during brief stops. Typically, pantograph chargers deliver a minimum power output of 450 kW.

The Brisbane Metro uses the TOSA (Trolleybus Optimisation Système Alimentation) Flash Charging System, which is a high-capacity pantograph system designed for rapid charging at end of line charging points and the depot. This is a specialized “Bus-up” system designed for High-Capacity BRT, see Figure 4.

Harmonics can have detrimental effects on EVSE, which can lead to performance issues, safety risks, charging interruptions or failures and increased operational costs. Harmonics are voltage or current waveforms at frequencies that are multiples of the fundamental power frequency. In the context of EVSE, harmonics typically arise from non-linear loads such as EV chargers, which use power electronics for charging control. Harmonic issues within EVSE should be analysed at the design stage, so EV chargers are designed with power electronics that generate less harmonic distortion and fully consider harmonic changes with both grid connection and vehicle integration across all operating conditions.

BIC suggests a decentralised outcomes-based approach to battery management, which recommends Bus Manufacturers provide a detailed overview of how battery management should be considered for their product/s. Bus OEMs should specify, as a minimum, the following High-Level Requirements: total energy (kWh), usable energy (kWh), energy buffer (kWh) (total energy minus usable energy), minimum percentage State of Charge (SOC), undercharging and overcharging prevention, battery degradation, charging curves and number of battery cycles (cycle life).

Figure 4. Brisbane Metro “Bus-Up” Pantograph Charging

Electric Vehicle Supply Equipment (EVSE) provides dedicated functions to supply electric energy from a fixed electrical installation or supply network to an EV for the purpose of charging. EVSE can include the following aspects:

1. Charging cables,
2. Connectors plugs,
3. Communication protocols,
4. Safety features,
5. Charger or inverter to convert AC from the grid to DC,
6. Transformers to adjust the voltage from the grid, and
7. Metrology systems for metering and billing

If used for commercial trade in electricity it must accurately determine the amount of active electrical energy supplied to or from an electric vehicle for billing purposes. EVSE shall be constructed so that an EV can be connected and in normal conditions of use, the energy transfer operates safely, and its performance is reliable and minimises the risk of danger to the user or surroundings. There are various interrelated international standards which govern EVSE. It is imperative that the standards and specifications of the charging infrastructure are established to accommodate the increasing transition to zero-emission buses (ZEBs) across many fleets and operations. BIC recommended EVSE standards including:

- General Safety Requirements (ISO 17409)
- EV Infrastructure (IEC 61851)
- Connectors and Cables (IEC 62196)
- V2G Communications (ISO 15118)
- Open Charge Point Protocol (OCPP 2.0.1)

- Australian National Measurement Institute (ANMI) Metrological Controls (OIML G22)

14. Hydrogen Refuelling Stations

Hydrogen-fuelled vehicles have been developed for decades, and recent renewable power generation cost savings have seen hydrogen refuelling stations (HRS) become more attractive. Effective planning, investment, and alignment with end goals are crucial for successful implementation.

HRS generally supply ZEBs with gaseous hydrogen at a pressure of 350 Bar as this meets the operating requirements for most buses that can generally return to depot to refuel. The considerable infrastructure costs for delivery at higher pressures mean that other technologies delivering hydrogen at higher pressures are less common for ZEBs.

Higher pressure HRS, offering 700 bar storage and refuelling allow for greater range on a vehicle, making it more applicable for long distance, heavy transport freight routes. HRS on freeway routes therefore will likely require the 700-bar option over 350 km, with the best example of this being the freight route between Melbourne and Sydney. Currently fast fill 700 bar refuelling is not enabled globally, so for any heavy vehicle refuelling, the slower fill time should be traded off with the longer range when deciding to implement such a HRS.

Cryogenic refuelling utilises liquefied hydrogen to refuel vehicles that require the fast delivery of large hydrogen quantities. However, very few refuelling stations like this have been implemented globally. In the future this may become possible but currently it’s unlikely to be implemented for ZEB use.

HRS dispensing systems must ensure that vehicles are fuelled without excessive risks that can include moving vehicles, hose breakaway, human factors as well as exceeding Hydrogen temperature and pressure limits. These systems should guard against control system faults that could cause hazards or damage to vehicles, as identified through risk assessments.

Dispensers at HRS can include additional monitoring equipment such as gas detection devices (or sniffers) and infra-red cameras to mitigate risks of dispensing H2. Such sensors are generally linked to the HRS delivery monitoring system that can alert operators to leaks and other scenarios that require suitable control measures to be taken. BIC recommended HSR standards include:

- ISO 19880 Gaseous Hydrogen - Fuelling Stations
- AS 22734:2020 Hydrogen generators using electrolysis
- IEC 60079 Explosive atmosphere standards
- US National Fire Protection Administration (NFPA)
- Fuel Quality (Grade D AS/ISO 14687)
- Equipment and Components (ISO 19880-1:2022)
- Electrical Safety for Hydrogen (AS3000, AS/NZC IEC60079)

15. Conclusions

Zero Emission Buses present a promising avenue for significantly reducing the carbon footprint of public transport and improving urban air quality. The BIC ZEB Advisories synthesize a wealth of best-practice insights that can be adapted to diverse operational contexts, effectively lowering the barriers to widespread ZEB adoption. By aligning national and international standards, the Australian bus industry can ensure interoperability, safety, and technological consistency.

Whilst the Advisories synthesise a significant body of knowledge further work is required, particularly in the Australian content in terms of energy optimisation, battery performance, hydrogen supply chain logistics, and total cost of ownership modelling. Future versions of the Advisories—and complementary research—could illuminate how ZEBs perform in varied duty cycles across metropolitan, regional, and remote areas, providing empirical data to guide policy decisions. Looking forward, several areas warrant deeper exploration and ongoing study, including:

1. **Lifecycle and Performance Data**: Collecting, sharing, and analysing long-term operational data from ZEB fleets will help refine maintenance schedules, battery degradation models, and residual value estimates.
2. **Grid Resilience and Demand Management**: As ZEB deployments increase, utilities and transit operators must collaborate on smart-charging strategies, demand response programs, and microgrid solutions that can mitigate the grid stress posed by large-scale fleet electrification.
3. **Hydrogen Infrastructure Scalability**: Further research on high-pressure (700 bar) and cryogenic hydrogen storage, distribution networks, and real-world refuelling throughput is critical to validating hydrogen's role for long-distance bus services and its compatibility with heavy freight vehicles.
4. **Economic and Policy Analysis**: Detailed cost-benefit analyses, including externalities (e.g., reduced health expenditures from improved air quality), can help policymakers and operators better quantify the true value of transitioning to zero emission fleets.
5. **Skill Development and Upskilling**: As technology progresses, training for both technicians and first responders must evolve; this calls for expansions to existing vocational programs and new micro-credentials focused on ZEB-specific competencies.

16. References

[1] L. Hardy, Bus and Coach Safety Advisory Electric Power Train Systems, Bus Industry Confederation (2024)
[2] M. Coleman, B. Coleman, Dr. J. Allwright, J. Upadhyay, Bus and Coach Safety Advisory Operations and Maintenance, Bus Industry Confederation (2024)
[3] M. Coleman, B. Coleman, Dr. J. Allwright, J. Upadhyay, Bus and Coach Safety Advisory Fixed Systems and Infrastructure, Bus Industry Confederation (2024)
[4] Department of Infrastructure, Transport, Regional Development, Communications and the Arts, "Vehicle Standard (Australian Design Rule 109/00 – Electrical Powertrain Safety Requirements)", 2018.
[5] Department of Infrastructure, Transport, Regional Development, Communications and the Arts, "Vehicle Standard (Australian Design Rule 110/00 – Hydrogen-Fuelled Vehicle Safety Related Performance)", 2018.
[6] ISO 6469-3:2021(E) Electrically propelled road vehicles – safety specifications – Part 3: Electrical Safety, 2021-10
[7] AS/NZS 3000:18 Electrical installations (known as the Australian/New Zealand Wiring Rules), 2018
[8] Australian Standards, AS 5732:2022 Electric vehicle operations — Maintenance and repair, 2022