Development of a Vehicle-to-Grid Testing & Demonstration Facility – Phase 1

Final Report

CSIRO and Essential Energy

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Glossary

AC: Alternating Current
A/C: Air Conditioner
ADR: Automated Demand Response
AI: Artificial Intelligence
API: Application Programming Interface
CEC: Clean Energy Council
CCS2: Combined Charging System
CHAdeMO: Japanese fast-charging system for electric vehicles
CSIP-AUS: Common Smart Inverter Profile – Australia
CSIRO: Commonwealth Scientific & Industrial Research Organisation
DC: Direct Current
DER: Distributed Energy Resources
DERMS: Distributed Energy Resource Management System
DOE: Dynamic Operating Envelope
EV: Electric Vehicle
EVSE: Electric Vehicle Supply Equipment
HACS: High Accuracy Current Sensors
HVAC: Heating, Ventilation, Air Conditioning
IEC: International Electrotechnical Commission
IEEE: Institute of Electrical and Electronics Engineers
IoT: Internet-of-Things
ISO: International Standards Organisation
NatHERS: Nationwide House Energy Rating Scheme
NMI: National Measurement Institute
OCPP: Open Charge Point Protocol
OEM: Original Equipment Manufacturer
PV: Photovoltaic
REIF: Renewable Energy Integration Facility
RMS: root-mean-square
SoC: state-of-charge
V2G: Vehicle-to-Grid
V2H: Vehicle-to-Home

Executive summary

Pilot Project Summary

This report presents the findings of a Vehicle-to-Grid (V2G) pilot demonstration project conducted by Essential Energy and CSIRO. The project aimed to develop an initial prototype of a V2G testing laboratory to explore the integration of V2G and electric vehicle (EV) technologies into homes, commercial buildings, and electricity networks. Specific objectives of the pilot phase of the project were:

1. **Prototype Facility Development**: Establish a flexible laboratory-based energy simulator to represent various household energy configurations and scenarios. This was proposed as the first step towards a fully developed V2G laboratory as part of a broader joint capability, combining Essential Energy's NEXUS facility in Port Macquarie and CSIRO's Renewable Energy Integration Facility (REIF) in Newcastle. This V2G capability is intended to be the most advanced in Australia for testing the integration of emerging energy and V2G technologies into homes and energy networks.
2. **Appliance-Level Monitoring and Control**: Implement an Internet-of-Things (IoT) enabled data acquisition and control system to monitor and control energy usage of individual household appliances and household distributed energy resources (DER) including solar photovoltaic (PV), batteries and bidirectional EVs.
3. **V2G System Integration**: Demonstrate the operation of commercially available CHAdeMO and Combined Charging System (CCS2) V2G capable chargers in a residential setup.
4. **Scenario Testing**: Simulate different energy and V2G use-cases to evaluate laboratory capabilities ensuring repeatability of experiments.
5. **Qualitatively assess V2G battery degradation**: Provide an initial assessment and benchmarks for battery degradation considerations in EV's when used for V2G applications.

Detailed household and appliance energy load profiles were modelled using CSIRO's residential energy simulation tools, representing typical household energy usage patterns under different household energy configurations and EV usage and charge/discharge scenarios. The modelled load profiles were used as targets to test laboratory simulations against, run over five days of testing.

Analysis of the simulations demonstrated that the initial prototype version of the V2G laboratory was able to accurately replicate the model target household load profiles and successfully integrate remote-controlled V2G, using both CHAdeMO and CCS2 bidirectional DC chargers. The pilot project has demonstrated the feasibility and potential benefits of integrating commercially available V2G technology into residential energy systems, and provides a solid foundation for future research and development and enhanced V2G laboratory capabilities.

Recommendations for Phase 2

Essential Energy and CSIRO have agreed in-principle to develop a long-term framework for the next phase of collaboration on the project, which will incorporate a staged approach to the development and use of the V2G laboratory over a 5-year extension to the partnership. Building on the achievements of Phase 1 outlined herein, a menu of possible options was developed outlining key areas for advancing the V2G laboratory capabilities and expanding the scope of V2G testing. The objective is to inform industry on approaches to V2G connections policy, market and regulatory implications of V2G at scale, alongside technical considerations.

Recommendations and a menu of proposed laboratory enhancements for consideration, discussion and prioritisation during the proposed next phase the project are summarised in six themes as follows:

Theme 1: V2G Laboratory Facility Development

The prototype V2G laboratory development proceeded further than was originally planned for the pilot project; however, further refinements of the basic infrastructure should be considered:

1. **Data Integration:** Standardise data formats and refine data acquisition systems for seamless assimilation and visualisation of captured data. This will enhance the accuracy and efficiency of data analysis.
2. **Automation:** Fully automate appliance scheduling and control to eliminate the need for manual interventions. Whilst there was minimal manual intervention during the test runs, the team did find further opportunities for automation. This will improve the reliability and consistency of the experimental simulations and also ensure repeatability.
3. **Expand Range of Appliances:** Incorporate additional appliances that reflect a wider range of modern all-electric household configurations. This will provide a more comprehensive understanding of household energy dynamics. Key items to consider include heat pump water heaters and space heating ventilation and cooling (HVAC) systems. Further expansion could consider controllable fans and alternative forms of thermal batteries such as pool heaters. Simulation of cooking loads is also recommended with a Wi-Fi enabled induction cooktop and electric oven.
4. **Enhance Load Metering and Control:** Develop a metering schema which enables independent simulation and metering of all minor household loads, such as lighting, cooking, and washing machines. This will ensure a more complete and detailed energy profile. Incorporate capability to manage household loads based on telemetry data and constraints such as production or price targets.
5. **Charger Control:** Implement more advanced control-loop functionality for EV charge and discharge variations based on real-time household energy flows, telemetry data, operating conditions and artificial intelligence (AI). This will enable simulation of intelligent energy management for the home - including more advanced capability with optimised load-following or grid-export discharge behaviour. This potentially provides Essential Energy with the technical knowledge to deploy EVs to outage areas as mobile generators.
6. **Discharge instead of driving:** Implement a system to automatically discharge EV battery to a set level in place of physically driving the vehicle to. This will streamline the testing process, especially for longer test runs over multiple days, and will enable easier simulation of different vehicle usage patterns.
7. **New Scenarios:** Develop and run new household scenarios and configurations to test enhanced laboratory capabilities. This will expand the range of use-cases and improve the robustness of the findings.
8. **Gateway Devices:** Gateway devices offer opportunities to control older assets and enable control over assets that have no native smart capability. The laboratory currently has several appliances with gateway-style connectivity, such as a pool pump and a resistive storage hot water system. It also has older inverters with a gateway present, allowing unique integration testing opportunities.
9. **Premise-level export and import management:** Develop capability to manage multiple household DER assets simultaneously including fixed batteries. The future home is likely to have several devices capable of both exporting to the grid and importing from the grid at levels unsustainable for the network without a level of management. A typical use-case is for premises with older 6mm (40A, 9kW) services. In these instances, a 7kW AC EV charging session combined with nominal household

loads could potentially overload the service. Equally, multiple devices exporting, such as rooftop solar and a V2G EV could exceed export limits and connection ratings.

10. **Extend abnormal network simulation capability:** Incorporate capability to test in abnormal network conditions including voltage and frequency excursions. Frequency shifting is emerging as a critical capability for microgrid solar inverter backstops. The impact on frequency shifting with V2G is a completely unexplored area and may have significant implications for system support in contingency events if frequency shifting affects V2G capability.

Theme 2: Incorporation of Emerging Technologies

1. **New V2G-Compatible Electric Vehicles:** Expand V2G laboratory capabilities in a technology-agnostic way to include new EVs with bidirectional capabilities, ensuring compatibility testing with a range of different bidirectional charging standards.
2. **CCS2 (Combined Charging System Type-2):** Include a wider range of CCS2 V2G capable vehicles and chargers when and as they become available to the market. This will support higher charging and discharging rates and enhance compatibility. It is noted that the laboratory currently has one type of advanced CCS2 V2G charger already installed but limited vehicle types to test this capability with at the time of writing this report.
3. **Support for AC and DC Bidirectional Charging:** Include both AC and DC configurations in laboratory tests to assess their feasibility for residential and commercial applications. The unique nature of the V2G laboratory facility is that equipment can be readily swapped out for testing. This capability means that the laboratory can help develop product capability without significant laboratory reworking.
4. **ISO 15118-20 (International standard for international standard for communication between EVs and charging infrastructure):** Upgrade laboratory systems to test the implementation and compatibility of ISO 15118-20 for both AC and DC bidirectional charging scenarios.
5. **OCPP 2.1 (Open Charge Point Protocol):** Upgrade laboratory systems to test the implementation and compatibility of OCPP 2.1 for bidirectional charging control.
6. **CSIP-AUS (Common Smart Inverter Profile – Australia):** Test EV and electric vehicle supply equipment (EVSE) systems' compliance with CSIP-AUS to evaluate their readiness for dynamic operating environments in an Australian context.
7. **IEEE 2030.5 (Smart Energy Profile 2.0- Standard for communications between the utilities and grid-connected consumers devices, including EV chargers):** Integrate IEEE 2030.5 [1] as part of laboratory simulations to ensure devices and DERs can respond to grid signals for load balancing and energy exports. Determine if there are any features in 2030.5 not implemented in CSIP-AUS that are applicable to V2G on vehicles and EVSEs developed for the global market.
8. **Open ADR:** Test Open Automated Demand Response (ADR) capabilities as another option for control of EVs and EVSEs in bidirectional charging configurations.

Theme 3: Enhancing Simulation Capabilities with EV Emulation

1. **EV and EVSE Emulation Techniques:** Introduce the CSIRO EV Emulator in CSIRO's REIF into the V2G laboratory ecosystem to enable the virtual simulation of a wide range of EV models and charging systems that are not yet physically available in Australia. This will improve the flexibility and breadth of testing options as the emulator can simulate charging and discharging loads of specific EV and EVSE models in software as well as monitor and analyse the full suite of communications and energy flows between EVs and EVSEs.

Theme 4: Long-term Testing and Modelling of Costs and Benefits

1. **Battery Degradation Strategies:** Test strategies to minimise, measure and monitor battery degradation during V2G operations, such as managed charging/discharging algorithms.
2. **Economic, Financial and Environmental Modelling:** Develop models to assess the potential economic, financial, environmental, and grid benefits of V2G integration in residential settings when rolled out at scale over the long term.

Theme 5: Advanced Features and Use-Cases

1. **Dynamic Pricing and Energy Arbitrage:** Simulate real-time market conditions in laboratory to test how dynamic pricing can influence V2G operations in households for cost savings and revenue generation.
2. **Regulatory and Market Disruption:** As V2G becomes a ubiquitous feature of network services, it will be equally important to frame market services and regulatory frameworks to develop the correct financial mechanisms for V2G. The natural evolution of V2G will also reshape the roles of market participants and necessitate role realignment. The V2G laboratory coupled with broader CSIRO research capability provides a unique testbed for exploring regulatory reform and market role definition around V2G.
3. **Load Balancing and Grid Support:** Include simulations of extreme grid conditions to validate V2G systems' capabilities in supporting grid stability.

Theme 6: V2G Certification

1. **Certification Pathway Development:** Create a roadmap and plan for the development of V2G certification capability for the V2G laboratory, ensuring regulator and stakeholder buy-in, and acceptance by industry nationally. This service could potentially be 'incubated' and grown in the V2G laboratory, starting from bidirectional charging demonstration partnerships for new bidirectional chargers, vehicles and associated technologies, and building this up to certification of fit-for-purpose operation of bidirectional charging for Australian networks. This certification could then be devolved to range of testing service providers.

These recommendations are options and are not prioritised. The aim is to enhance the V2G laboratory's functionality, incorporate emerging technologies, and expand the scope of V2G testing to ensure cutting edge research and development to support and accelerate the clean energy transition in Australia.

1 Pilot Project Introduction and Objectives

CSIRO has partnered with Essential Energy, one of Australia's largest electricity distribution networks, to assist in developing an advanced V2G testing laboratory. The V2G laboratory's purpose is to explore how V2G and associated EV technologies can be safely and effectively integrated into homes, commercial buildings and electricity networks.

The pilot demonstration phase of this partnership aimed to develop an initial prototype version of the V2G laboratory capable of simulating the dynamics of a modern household energy system. Using both CHAdeMO and CCS2 charging technologies, the prototype laboratory explored scenarios where EVs act as both consumers and providers of electricity, enabling households to optimise local energy generation and usage, and potentially earn revenue for supporting grid stability.

The project objectives were as follows:

1. **Prototype Facility Development**: Establish a flexible energy simulator capable of replicating a range of household configurations, incorporating real-world appliances and solar generation.
2. **Appliance-Level Monitoring**: Implement a data acquisition system to monitor and control appliances and capture energy usage data.
3. **V2G System Integration**: Demonstrate the operation of available bidirectional chargers in a residential setup, enabling both energy self-consumption behind-the-meter and grid exports. Test the feasibility and practicality for implementation at scale of different approaches and platforms for remote control of bidirectional charging.
4. **Scenario Testing**: Simulate various energy and EV use-cases, including realistic typical residential load profiles, to evaluate system performance under different conditions.
5. **Recommendations for Further Development of V2G Laboratory:** Develop a menu of options and a series of recommendations for a 5-year development of the V2G laboratory under the next phase of the project, beginning in 2025.

This initial pilot project serves as a critical technical capability foundation for the proposed future work, and also as a stand-alone demonstration of the feasibility and value of V2G technology in Australian homes.

2 Partner Statements

2.1 CSIRO

As Australia's national science agency, CSIRO is well positioned to support industry and government in catalysing Australia's energy transition towards net zero emissions.

We partner with local and global companies, state and federal governments, and a broad network across the international innovation sector, to deliver energy solutions for a sustainable and prosperous future. These partnerships are based around provision of scientific testing and services, development of in-business science capability for innovative SMEs, longer-term fundamental research partnerships, and strategic alliances.

We work with our partners on research that aims to:

- Improve the affordability, reliability and grid integration of renewable energy technologies, including EVs, solar, wind and biofuels.
- Provide the transport sector with low and zero-emissions technologies and energy storage solutions.
- Improve the way Australia uses energy at home and at work through new household technologies as well as improvements in the operation of our electricity grid.
- Provide government and industry with the tools, data and modelling capability to inform policy assessment and investment decision-making.

Our facilities in energy systems research, which can be accessed by our partners, include our Renewable Energy Integration Facility (see Figure 1), large-scale solar demonstration facilities, our Stored Energy Integration Facility, and Vehicle Energy Integration Facility, which incorporates our EV/EVSE Emulator equipment.

Figure 1 - Renewable Energy Integration Facility (REIF).

To learn more about our diverse portfolio of research see: www.csiro.au/energy

2.2 Essential Energy

Essential Energy builds, operates and maintains one of Australia's largest electricity distribution networks, providing a vital service to over 900,000 customers across regional, rural and remote communities. Our network footprint covers 95 per cent of New South Wales and parts of southern Queensland, traversing 737,000 square kilometres of diverse landscape from the desert to the coast, across alpine to sub-tropical.

Our network covers vast areas with long spans of mainly overhead powerlines with less customers per power pole compared to our city-based counterparts. As the cost of maintaining the electricity network is shared across all customers, the transition to renewable electricity generation and decentralised energy services offers our communities the opportunity to increase power resilience and reliability as well as potential economic benefits.

Technology trials are vital to our ability to provide these opportunities for our customers. Innovation and technology advancement is made possible through strong working relationships with partners seeking to achieve similar goals. Our partnership with CSIRO aims to understand how technology can be part of a comprehensive home electricity management system to provide customers with better control over their energy usage and the opportunity to get better value from their renewable investments.

Supporting our customers through the energy transition and maximising the potential benefits for our regional, rural and remote communities are driving factors behind the development of the Innovation Hub in Port Macquarie with a particular interest in rapidly developing V2G capability.

3 V2G Laboratory Description

3.1 Overview

The V2G laboratory is being developed by Essential Energy and CSIRO to simulate the energy dynamics of a typical Australian household while integrating bidirectional EV charging capabilities. The prototype version of the laboratory described in this report incorporates state-of-the-art appliances, and two V2G configurations: 1) CHAdeMO: Nissan Leaf EV, and Wallbox Quasar bidirectional DC charger; and 2) CCS2: AUSEV Ford F-150 Lightning (right hand drive conversion for Australian market by AUSEV), and a development version of Sigenergy's DC bidirectional charger. The V2G laboratory design allows for flexible testing of household energy scenarios and accommodation of a range of V2G technologies.

The V2G laboratory is physically located at Essential Energy's Port Macquarie site. It forms part of Essential Energy's broader laboratory facilities encompassing a variety of capabilities and is organised into deployment phases as shown in Table 1 below. Future development of the V2G laboratory, detailed in Section 10, will also incorporate specialised testing capabilities from CSIRO's REIF laboratories in Newcastle.

Table 1 - Essential Energy laboratory deployment phases

Quality Assurance Laboratory	
Phase 1 & 2 – Quality Assurance (QA)	• Materials testing • Destructive testing • Accelerated aging
Phase 3 - Internet of Things (IoT)	• Customer Energy Resources (CER) Interoperability • Inverter testing • Asset orchestration and energy optimisation (HEMS) • V2G testing

Key features of the V2G laboratory include:

- **IoT-enabled Appliance Simulation and Integration**: Real-world household appliances, equipped with IoT smart controls enable the creation of realistic energy demand profiles.
- **Renewable Energy Integration**: A configurable PV array replicates on-site solar energy generation.
- **Dynamic Environment Control**: The laboratory simulates diverse climate conditions to match seasonal variations in energy usage.
- **Interoperability**: The facility leverages open-source platforms and protocol-agnostic frameworks to ensure adaptability to emerging energy technologies.

This unique facility provides a controlled environment for testing V2G functionalities and energy management strategies in an ecosystem that can accurately simulate household energy behaviours.

An overview of the laboratory is provided in Figure 2 and the experimental circuit and sub-circuits of the laboratory are illustrated in Figure 3. Photos of the Laboratory are shown in Figure 4, Figure 5 and Figure 6.

3.2 Laboratory Architecture

The laboratory employs an open-source, protocol-agnostic, modular architecture to enhance its adaptability to incorporate emerging technologies, including, for example, IEEE 2030.5 [1], OCPP 2.1 [2] and Open ADR [3]. The architecture can be summarised as follows:

- **Central Control System**: Home Assistant serves as the primary control interface, orchestrating the operation of all connected devices, including the Wallbox Quasar [4] bidirectional charger, smart appliances, and energy storage systems. This reflects the growing role and importance of home energy management systems (HEMS) in managing increasingly diverse energy ecosystems within households.
- **Data Acquisition Infrastructure**: A combination of Satec [5] power meters and IoT sensors collect granular data on energy flows, voltage, and current from appliances and the grid.
- **Dynamic Messaging and Device Management**: Borrowing from Distributed Energy Resources Management System (DERMS) concepts, the laboratory employs telemetry hubs to monitor device states and manage energy constraints dynamically. This system is designed so that it will in future be able to process real-time grid signals and adapt operations based on simulated network needs.
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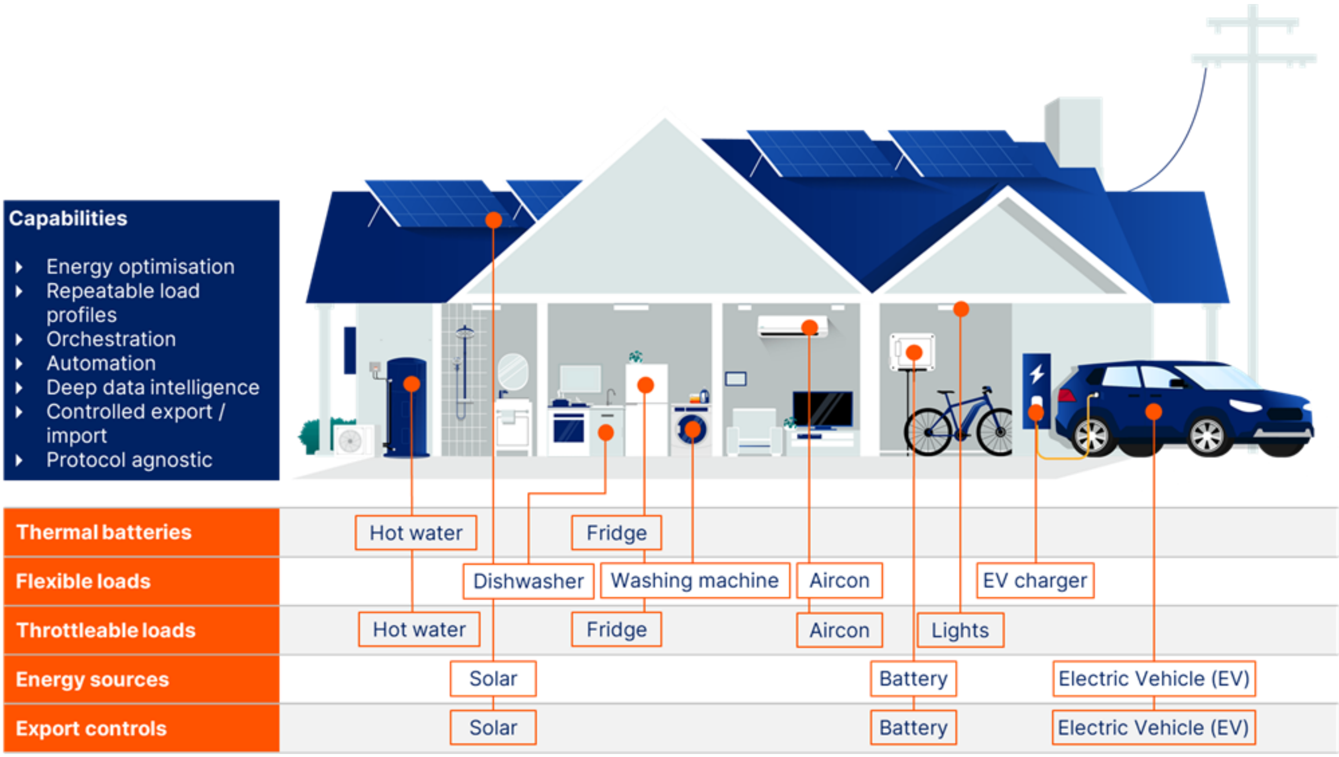


Figure 2 - Overview of the V2G laboratory.

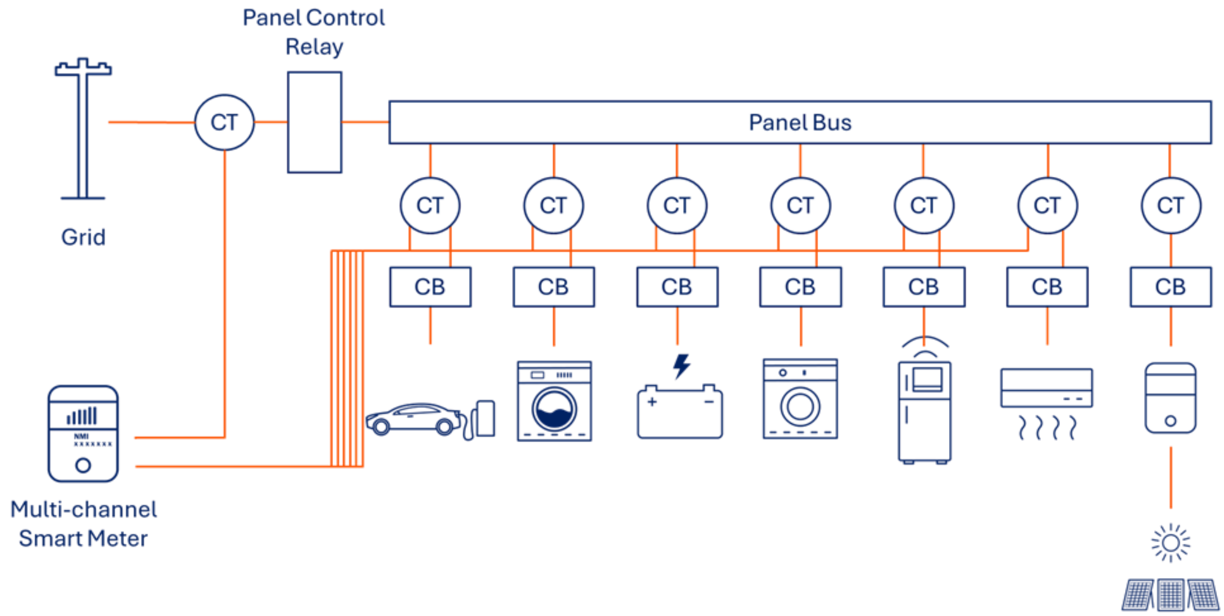


Figure 3 - V2G laboratory experimental setup.

Figure 4 - Photos of the V2G laboratory: Household Simulator

Figure 5 - CHAdeMO V2G using Nissan Leaf and Quasar Wallbox DC charger

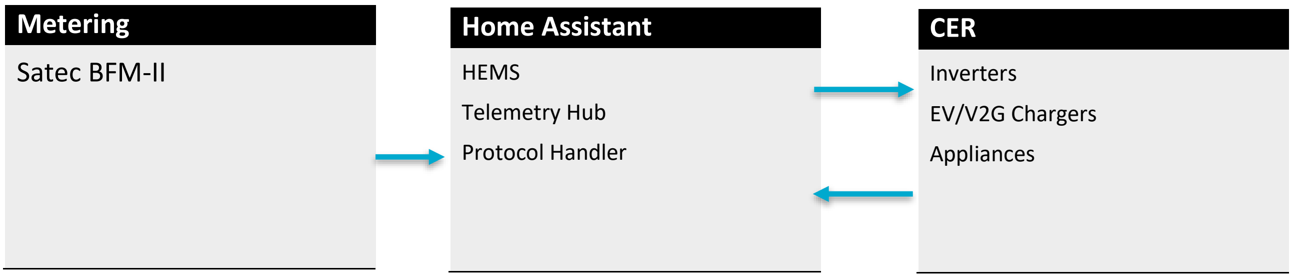
Figure 6 - CCS2 bidirectional charging using AUSEV Ford F-150 Lightning and Sigenergy DC charger.

4 Data Acquisition and Control System

4.1 Introduction

The V2G laboratory's data acquisition and control system serves as the backbone for monitoring, managing, and analysing energy flows within the V2G test environment. The system combines advanced hardware and open-source software to deliver high-resolution data and robust control over appliances and EV charging systems. The data acquisition and control system includes the following key components:

- Home Assistant software
- Home Assistant Green hardware
- Satec BFM-II NMI power meter (w/ high accuracy current sensors)
- Telemetry Hub



The next sections briefly describe these key components and how the data acquisition and control system components work together.

4.2 Home Assistant Software

Home Assistant is an open-source software home automation platform that allows users to control and automate various smart appliances/devices within their homes [6]. It provides a home-centralised interface for managing a wide range of smart home devices, making it easier to create custom automations and routines. Here are some key features of Home Assistant:

Automation: Create complex automations that trigger actions based on various conditions, like time of day, device states, or sensor readings. Node-Red automation software can also be installed within Home Assistant.

Technology Agnostic: It supports a diverse array of communication protocols and over 1,000 integrations, allowing users to connect devices from different manufacturers and platforms such as Apple HomeKit, Google Home, Samsung SmartThings, and Amazon Alexa.

Local Control: Home Assistant operates locally, ensuring data remains private and can function without internet connectivity. Exposure to the cloud is optional, and the V2G laboratory has a hybrid local and cloud control approach to its implementation of Home Assistant.

Flexible Interface: Home Assistant provides a web-based dashboard that can be accessed from any device, making it easy to display data, monitor and control from a variety of platforms.

Open-Source: Continuous improvements, customisations and new features are contributed to by a large global community of developers and users that the research teams can access.

Figure 7 shows the Home Assistant dashboard for the V2G laboratory.

Figure 7 - Home Assistant Dashboard for the V2G laboratory.

4.3 Home Assistant Green Hardware

Home Assistant Green, as shown in Figure 8, is a hardware device that comes pre-installed with Home Assistant software [7]. It simplifies the setup process and enhances automation capability by providing a dedicated platform for managing smart home devices.

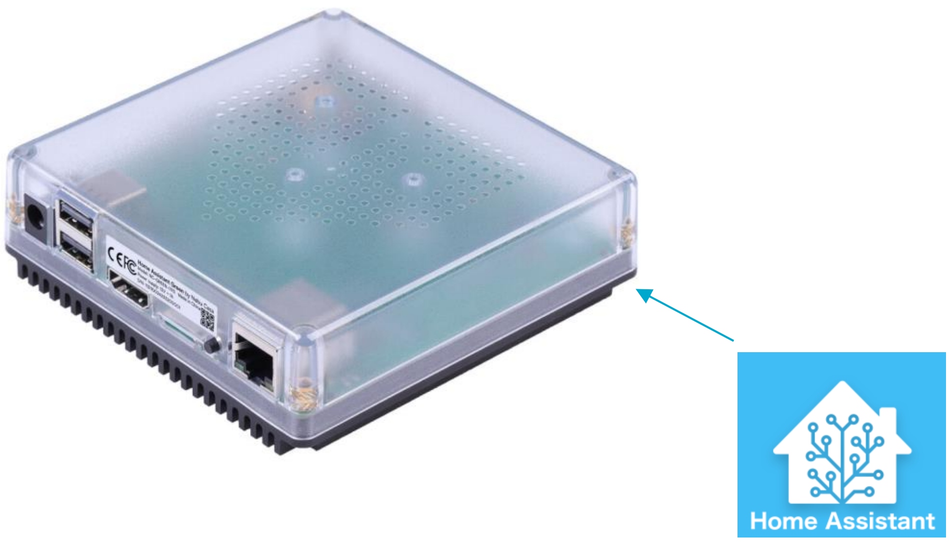


Figure 8 Home Assistance Green (hardware) with Home Assistance (software) [6].

Key features of Home Assistant Green include:

Easy Setup: Designed to be plug-and-play, requiring minimal setup effort.

Powerful Hardware: Comes with a quad-core Arm Cortex-A55 CPU, 4GB RAM, and 32 GB eMMC storage to handle multiple smart home appliances and complex automation.

Integration of Technologies and Protocols: Supports the same wide range of integrations as the Home Assistant platform such as Wallbox Application Programming Interface (API), OCPP, GE Home (SmartHQ), LIFX, Matter, Mill, OpenWeatherMap, PurpleAir, Shelly, SMA Solar, Solcast PV Forecast, Starlink, Apple Thread, HomeKit, Google Home, TP-Link Tapo, ZigBee Home Automation, etc.

Local Control: Maintains the privacy and reliability of local control.

Expandability: Through third-party USB accessories, additional smart standards like Zigbee, Z-Wave, and Bluetooth can be enhanced.

Modbus Controller: It comes with a pre-configured Modbus server that is ready to use.

Remote Access: Remote access is built into the Home Assistant instance and allows secure access from anywhere using a unique remote URL and security certificate. This allows researchers to debug and fix issues remotely if required.

In summary, Home Assistant Green combines the flexibility and functionality of Home Assistant software with the convenience and reliability of a dedicated hardware platform.

4.4 Satec BM-II Power Meter

The Satec BFM-II (Branch Feeder Monitor) power meter – as shown in Figure 9 – is a multi-circuit power meter designed for energy management in various applications, from medium-voltage substations to commercial multi-tenant billing. This power meter was selected for this project because CSIRO researchers are familiar with the hardware and find its user interface easy to use. Additionally, it can measure electrical voltage and current waveforms for sampled at a rate of 64 samples per cycle (or 3.2kHz) for eight cycles every 10 seconds, which will be useful in the planned Phase 2 future work.

Some key features of the Satec power meter are as follows:

Multi-Circuit Metering: It can monitor up to 18 three-phase power circuits, 54 single-phase circuits, or any combination of the two.

High Accuracy Current Sensors (HACS): These sensors measure and report the current consumed by each branch circuit with high precision. Each HACS is calibrated to meet Class 0.2S active energy and Class 0.5S reactive energy meter accuracy.

Built-in Communication Ports: It comes equipped with RS485, Ethernet, and an optional 4G modem, supporting protocols like BACnet, Modbus RTU/TCP, DNP3.0, and IEC 60870-5-101/104.

NMI Grade Meter: NMI-approval is pending, and the meter meets Australia’s legal requirements, having been tested by the National Measurement Institute (NMI). Certified approval is expected in 2025.

Digital & Analog I/O: It supports up to 72 digital and 16 analogue inputs, allowing for comprehensive energy management solutions.

Figure 10 provides a detailed representation of a standard electrical installation designed for wiring six channels of 3-phase current input. For the laboratory, each channel is configured to ensure optimal performance and safety while measuring single-phase electrical power for each appliance under test, as illustrated in Figure 11.

Figure 9 - Satec BFM-II Power Meter (left) with a Modbus TCP interface and a HACS 100A (right) [5].

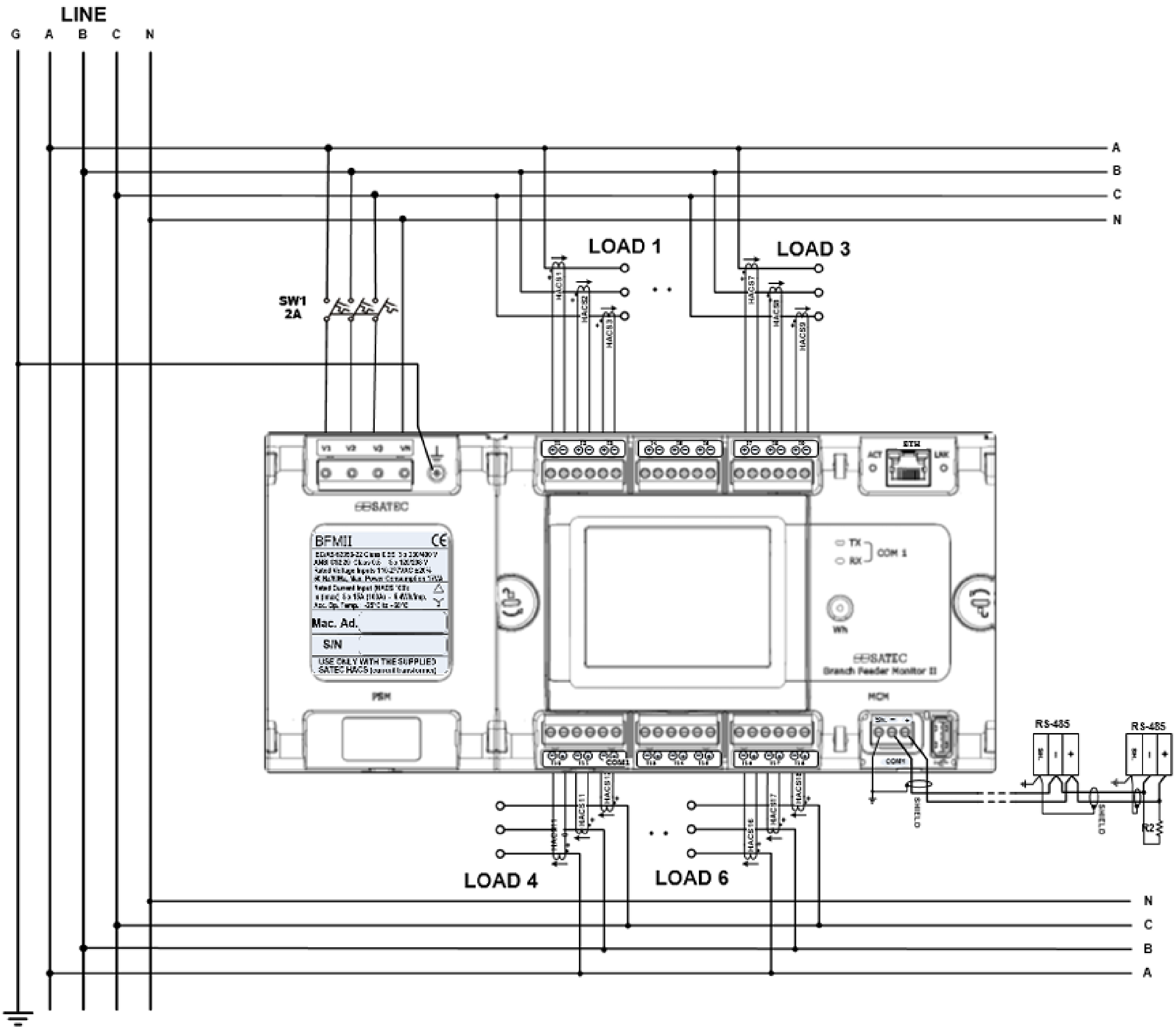


Figure 10 - Typical electrical installation for 6x 3-phase current input channels wiring [5].

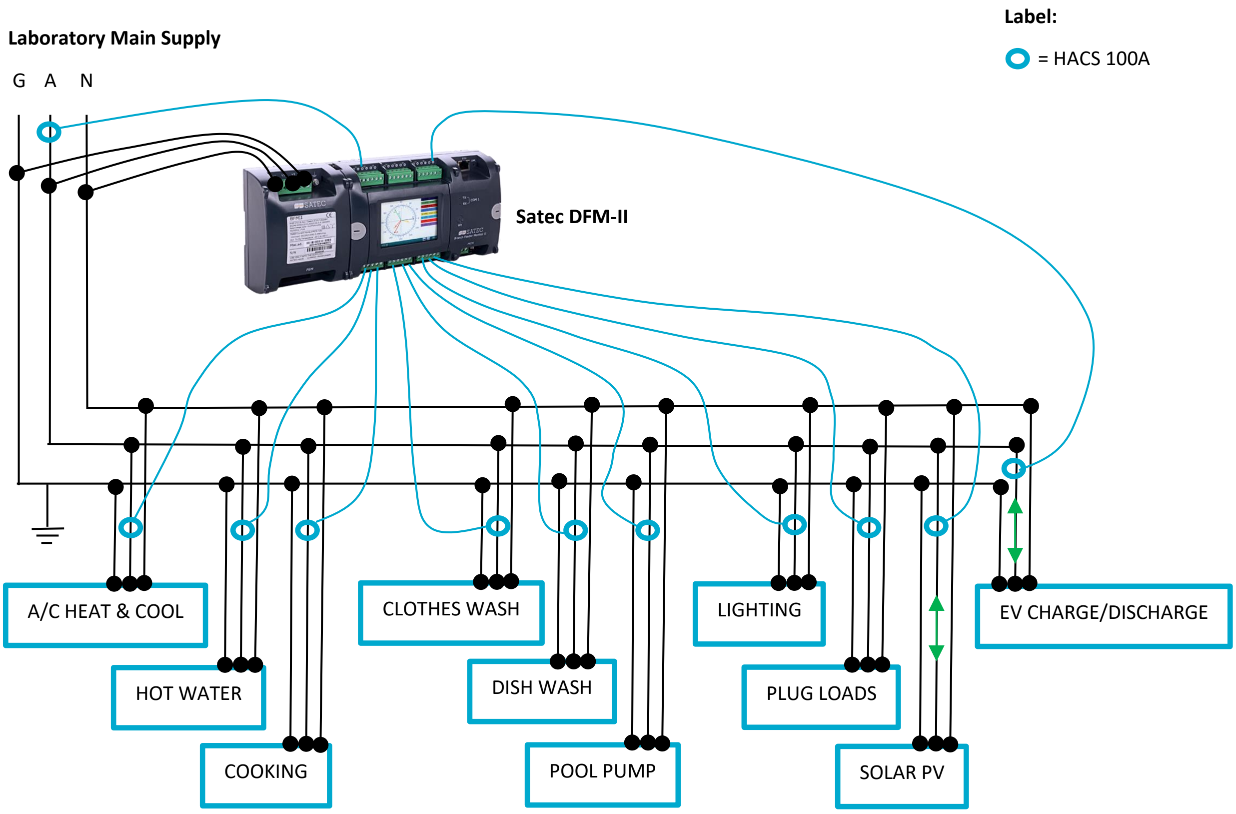


Figure 11 - Satec BFM-II 100A HACSs (blue circles) of the laboratory appliances.

4.5 Telemetry Hub

The V2G laboratory integrates a DERMS-compatible telemetry hub to process data from smart devices and respond to network signals. This hub enables:

Dynamic Constraint Management: Devices like solar inverters and EV chargers can adjust their export and import settings based on network conditions.

Data Consolidation: The hub aggregates data from multiple sources, supporting advanced analytics and event logging.

4.6 Data Flow, Control and Connectivity

The overall laboratory system data flow, control and connectivity operate as follows:

Real-time Monitoring: The Satec power meter's HACS are connected to individual circuits – as shown in Figure 11 – to capture appliance-specific energy metrics every fifteen seconds using a built-in Modbus industrial controller. The data collected includes the root-mean-square (RMS) voltage, current, energy and power, and it is stored in its SQLite database for analysis and reporting. Additionally, the data is backed up to Google Drive to protect against potential system crashes or data corruption.

Control Automation: Using preconfigured automation scripts, Home Assistant dynamically adjusts appliance and EVSE operations to meet target load profiles and grid requirements. Automation includes control over appliances' on/off status or adjustment of setpoints according to the test schedules developed, as described in Section 6 of the report.

Grid Interaction: The control system architecture is intended to be future proofed to allow incorporation of DERMS-inspired features, such as telemetry-based dynamic operating envelopes (DOEs), to align household energy consumption and exports with network constraints and conditions.

Ethernet Connectivity: The main components of the data acquisition and control system connect via Ethernet to the laboratory's Starlink connection, which serves as the local backbone as well as a gateway to the internet, as illustrated in Figure 12. The laboratory appliances are either integrated locally or via the appliance cloud API. For example, the Wallbox Quasar bidirectional charger connects to the Wallbox API's cloud service [8] allowing full remote control.

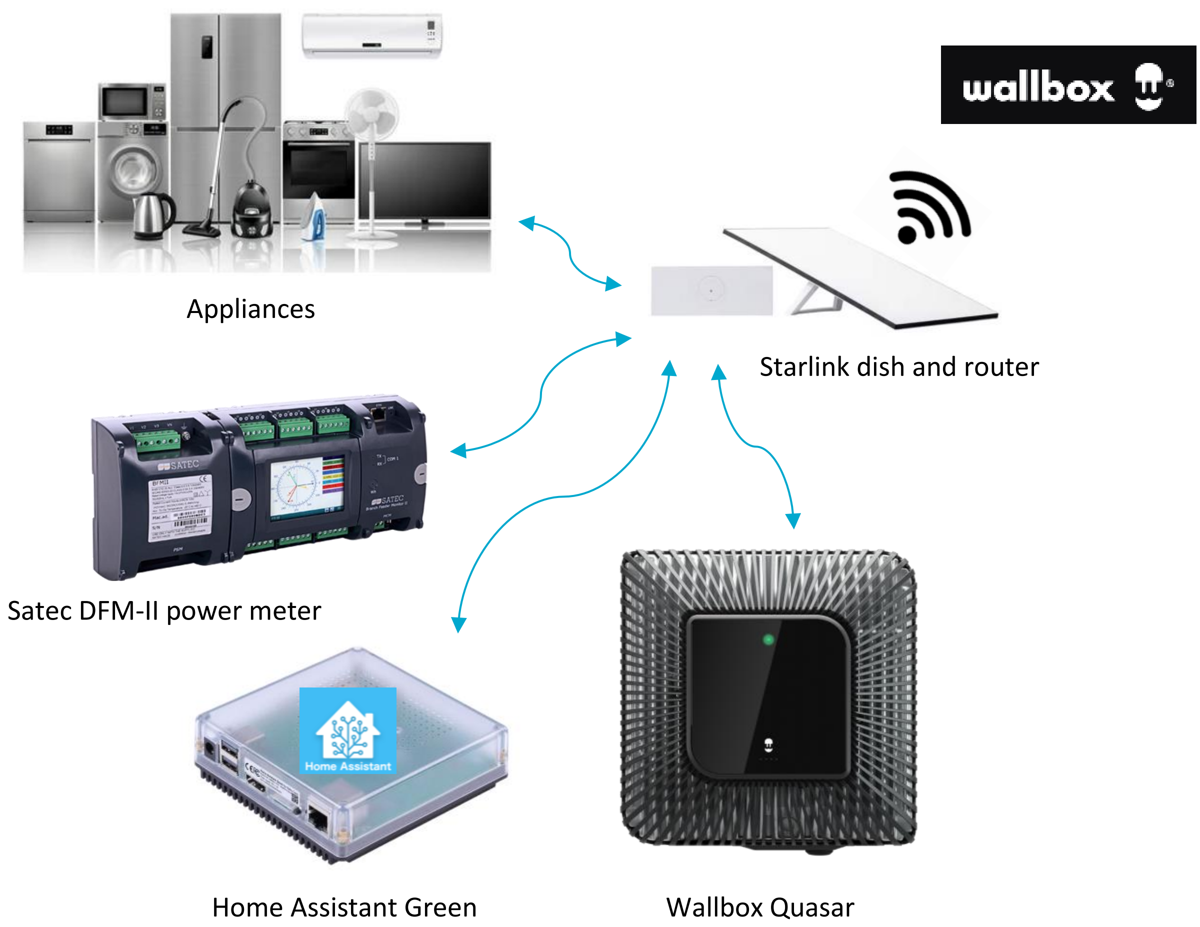


Figure 12 – Ethernet connectivity for the V2G laboratory.

5 Modelling Typical Household Load Profiles

5.1 Introduction

To test the V2G laboratory's capabilities, detailed household and appliance energy load profiles were modelled using the benchmark energy rating software tool of the Nationwide House Energy Rating Scheme (NatHERS) [9] which was developed by CSIRO. These profiles served as benchmarks for the laboratory simulations, representing typical household energy usage patterns under different EV use-cases. The modelled profiles were used to create a set of target load-profiles for the laboratory experiments, and also to visualise realistic appliance loads and their relative sizes and timings, which in turn was used to help design methods and priorities for implementing automation capabilities in the laboratory.

The load profiles were developed on an hourly basis over an entire year, to enable capturing seasonal variations in energy demands. These simulations provided insights into appliance-specific loads and informed the initial design of the laboratory's automation algorithms and testing processes.

Description of the household model, the predicted appliance load profiles for each month of the year and projected typical daily load profiles are outlined in the following sections.

5.2 Home Layout and Configuration

The modelled household represents a modern, energy-efficient family home built in Port Macquarie. The north-facing floor plan, designed with a 6-Star NatHERS energy rating, features:

- Configuration: A four-bedroom house with all-day occupancy by a family with young children.
- a 6 kW Solar System
- Medium size swimming pool with single-speed pump
- Reverse-cycle air conditioner (A/C) heat pump for heating and cooling.
- Heat pump hot water system.
- Induction cooktop and electric oven

While the pilot-project configuration of laboratory does not currently have a heat pump water heater or inductive cooktop, the load profiles for these assets were simulated in the pilot phase of the project using a combination of a resistive water heater and an oil-filled room heater.

This setup reflects the energy profile of a typical Australian household, enabling a realistic simulation of energy usage. The floor plan is shown in Figure 13.

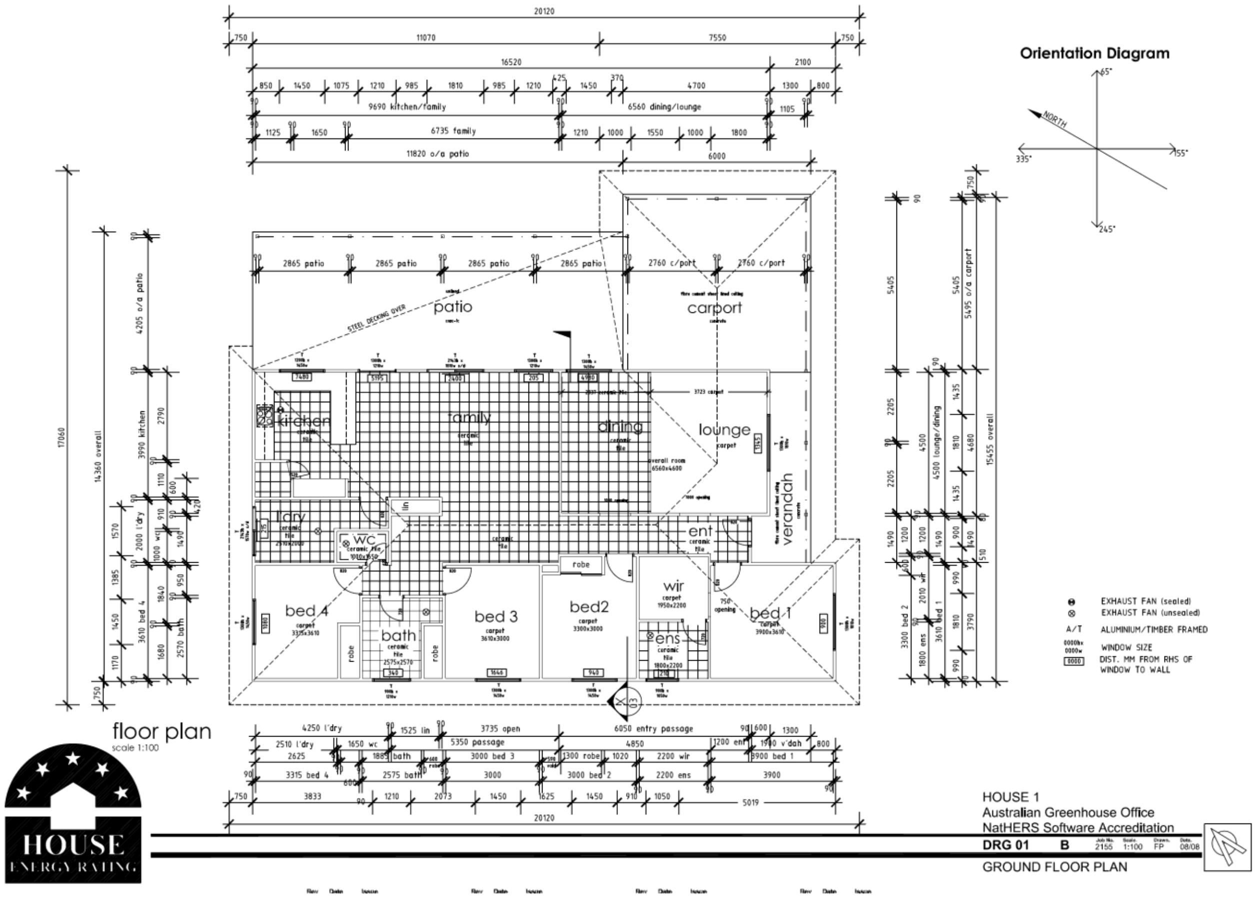


Figure 13 - Floorplan of 6-Star all-electric family home used to model appliance load profiles.

5.3 Predicted Appliance Loads

Predicted appliance loads for the family house as configured above were calculated using CSIRO models, and real weather data for Port Macquarie. Hourly data for a full year was generated.

The appliances chosen for the model are based on commonly installed appliances in new energy-efficient electric homes. The modelling results provided the baseline for the development of different target profiles for laboratory testing.

Results from the NatHERS modelling of the Port Macquarie home are shown in Figure 14 and Figure 15. Figure 14 outlines the monthly average profiles for total household consumption, predicted solar generation and the largest of the appliance loads which include heating, cooling, hot water and pool pump. Figure 15 outlines the minor appliance loads, including lighting, cooking, and combined plug loads incorporating clothes washing and dishwasher grouped together.

These profiles provided a robust foundation for development of laboratory testing scenarios, providing an accurate replication of typical energy usage patterns.

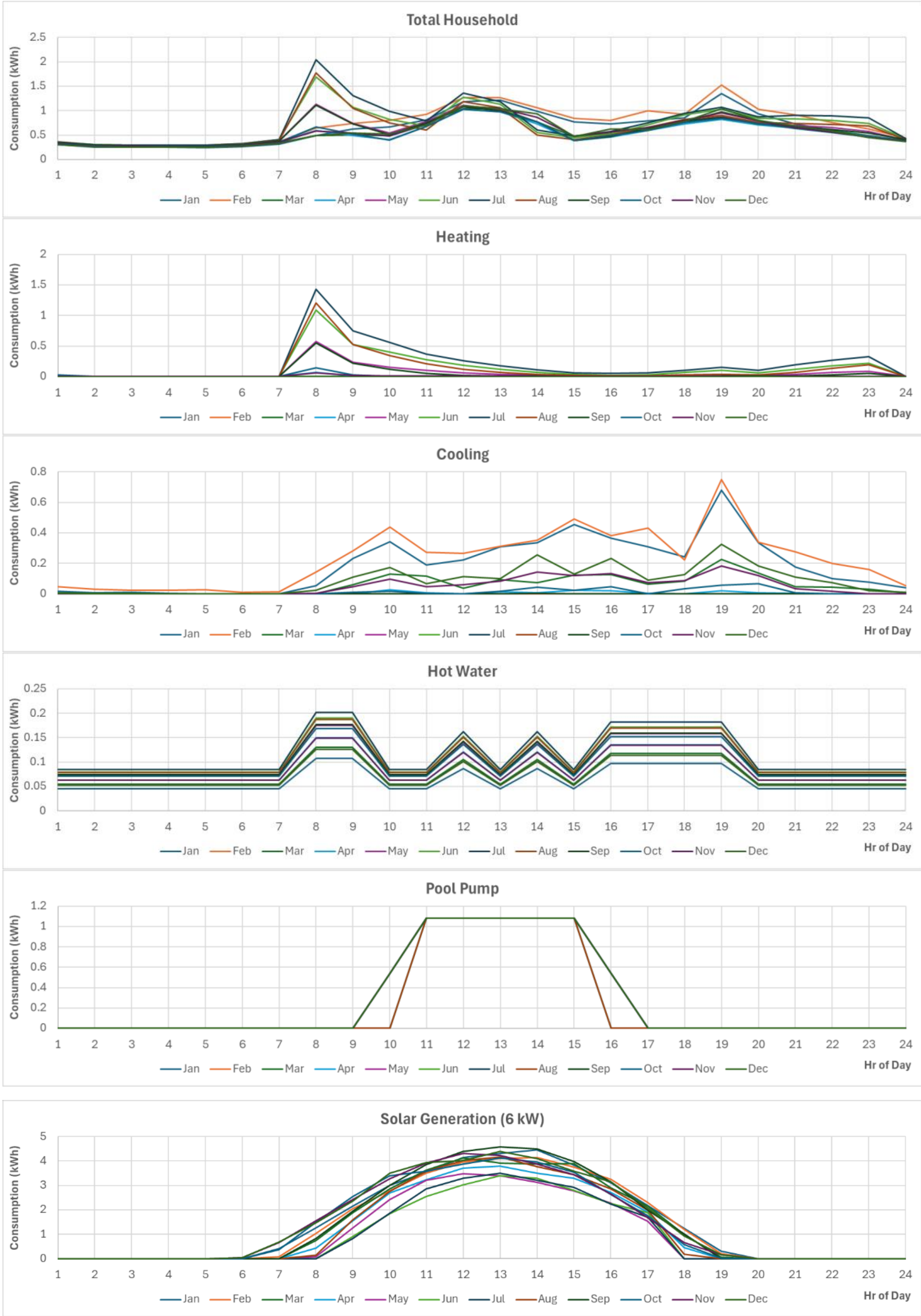


Figure 14 – Average daily load profiles for total household consumption, solar generation, and the most significant appliance loads for heating, cooling, hot water and pool pump.

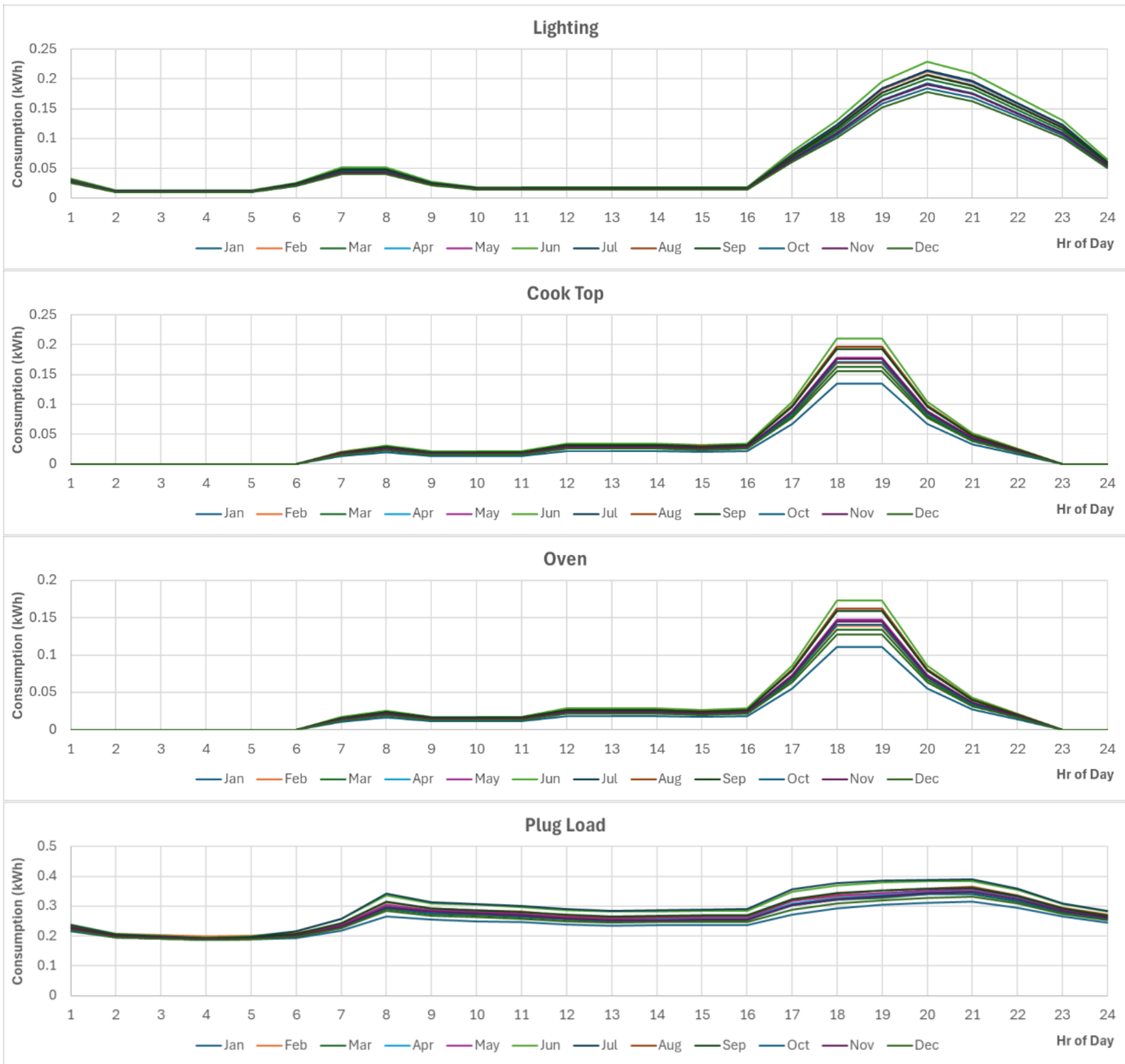


Figure 15 – Average daily load profiles for minor appliance loads - lighting, cooking, and combined plug loads incorporating clothes washing and dishwasher.

6 Target Scenarios and Charge/Discharge Algorithms

6.1 Introduction

Four primary scenarios incorporating different household energy and EV use-case configurations were developed. These were used as 'target' load profiles for the V2G laboratory to simulate, and also as the basis for testing and development of the laboratory capabilities such as appliance automation, data acquisition, and V2G operation.

The four scenarios incorporated different climates, home-based and commuter vehicle usage patterns, and different charge-discharge algorithms. Note that these scenarios were selected to illustrate informative and contrasting V2G load profiles and not as the most "optimal" or "typical" V2G use cases.

6.2 Scenario 1: Winter climate, Commuter EV, overnight charging, daytime pool pump

Scenario 1 represents a household with a commuter EV that charges overnight using off-peak electricity and discharges during evening peak periods. Key details include:

Vehicle Usage: The Nissan Leaf EV covers a 100 km daily commute and evening discharge, requiring approximately 60% of its 62 kWh battery capacity for both driving and evening discharging.

Energy Usage Patterns:

– EV charging and water heating occur overnight.

– The pool pump operates during the day using solar energy.

The peak grid load reaches approximately 6 kW overnight due to EV charging, with net-daily usage of around 13 kWh when solar generation is included.

The modelled profile plot and table of values for this scenario are presented in Figure 16. This scenario was not simulated in the laboratory due to time and vehicle constraints and will be carried over to the Phase 2 research.

6.3 Scenario 2: Winter climate, Home-based EV, solar charging, overnight pool pump

Scenario 2 represents a household where the EV remains home-based and prioritises solar self-consumption for charging. Key adjustments include:

Vehicle Usage: Limited to 40 km daily for school drop-offs and pick-ups, consuming 40% of the EV battery capacity for both driving and discharging in the evening.

Energy Usage Patterns:

– The EV charges during the day using solar PV generation and discharges in the evening.

– The pool pump operates at night using off-peak electricity.

The net export from V2G in the evening allows the household to offset peak demand for other customers or earn income at the time of peak prices.

Net daily grid usage is minimised to around 2 kWh, prioritising energy self-sufficiency.

Profile plot and table of values for this scenario are presented in Figure 17.

6.4 Scenario 3: Spring climate, Home-based EV, solar charging, daytime pool pump

Scenario 3 is similar to Scenario 2 but uses a spring climate and modified pool pump operation. Key details include:

Energy Usage Patterns:

- The pool pump runs during the day using solar energy.
- Peak grid demand occurs midday during EV charging.

The household achieves net energy export to the grid of approximately 8 kWh daily, demonstrating efficient energy management as well as a grid contribution and a small potential revenue for the household.

Profile plot and table of values for this scenario are presented in Figure 18.

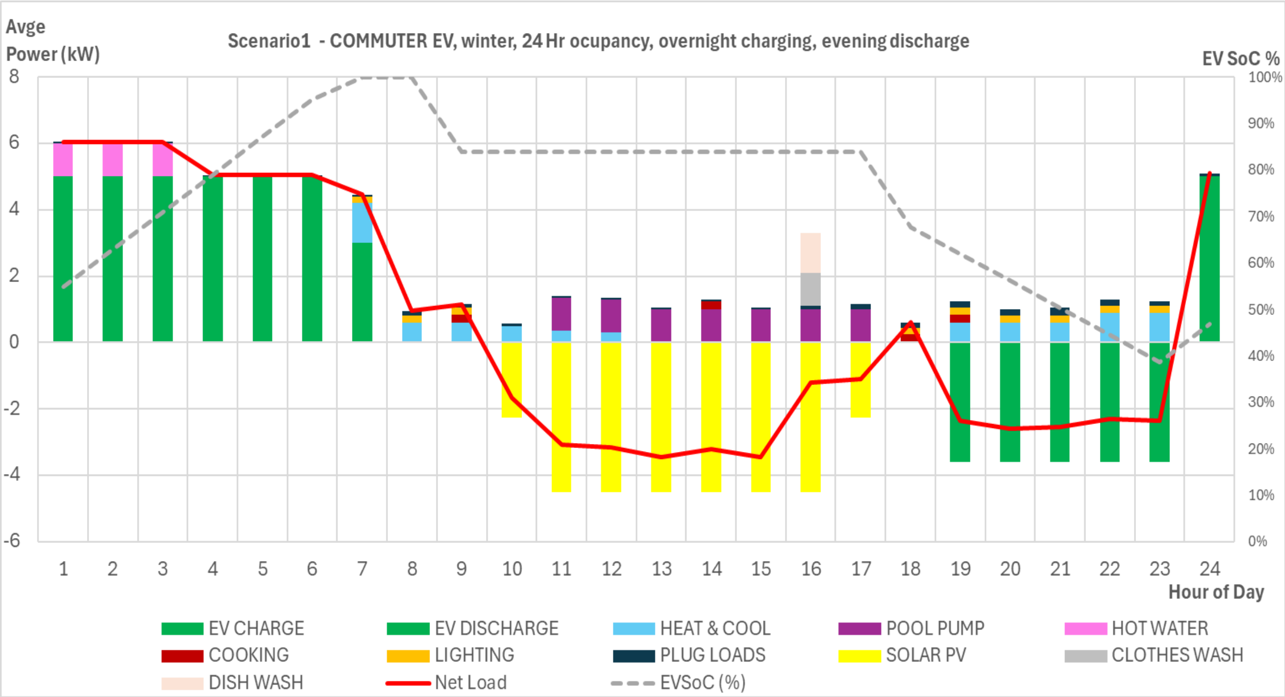
6.5 Scenario 4: Net-zero load-following demonstration

Scenario 4 was designed as an initial test and demonstration of the load following capability of the CCS2 bidirectional charging configuration. Key details include:

Energy Usage Patterns:

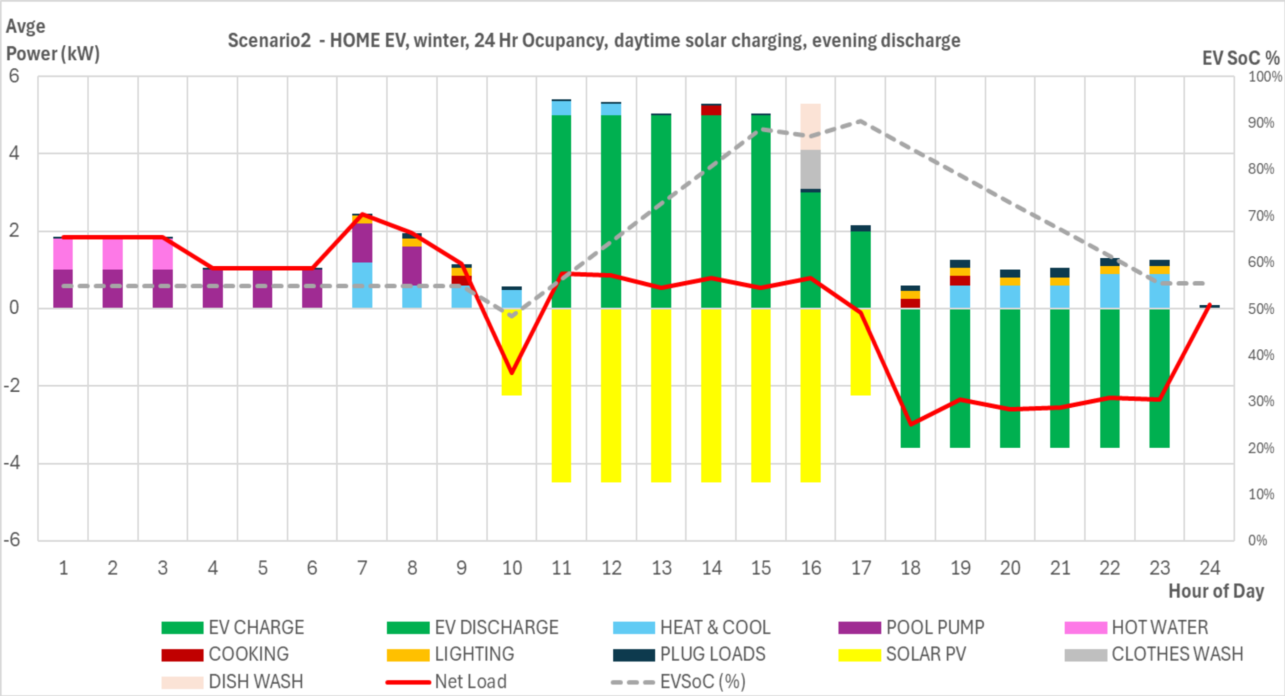
- The pool pump runs during the day using solar energy.
- Lighting, cooking and plug loads are not included and the EV was not driven.
- The CCS2 charger is set to charge and discharge variably to target zero import/export.

Profile plot and table of values for this scenario are presented in Figure 19 – Scenario 4 target .



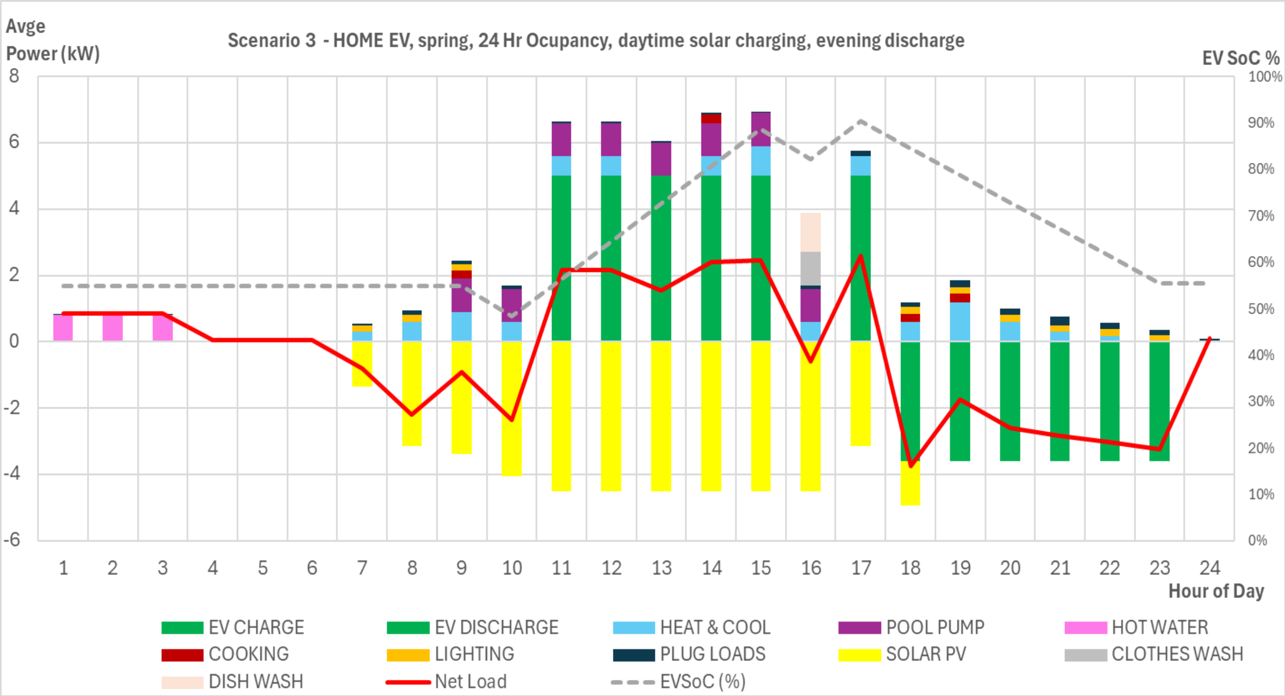
Hour	TOT (kWh)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Net Load	**13.09**	6.05	6.05	6.05	5.05	5.05	5.05	4.45	0.95	1.15	-1.67	-3.09	-3.15	-3.45	-3.2	-3.45	-1.2	-1.1	0.6	-2.35	-2.6	-2.55	-2.3	-2.35	5.1
HEAT & COOL	**7.14**	0	0	0	0	0	0	1.2	0.6	0.6	0.48	0.36	0.3	0	0	0	0	0	0	0.6	0.6	0.6	0.9	0.9	0
HOT WATER	**3**	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
COOKING	**1**	0	0	0	0	0	0	0	0	0.25	0	0	0	0	0.25	0	0	0	0.25	0.25	0	0	0	0	0
CLOTHES WASH	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
DISH WASH	**1.2**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.2	0	0	0	0	0	0	0	0
POOL PUMP	**7**	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0
LIGHTING	**1.8**	0	0	0	0	0	0	0.2	0.2	0.2	0	0	0	0	0	0	0	0	0.2	0.2	0.2	0.2	0.2	0.2	0
PLUG LOADS	**2.45**	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.15	0.1	0.1	0.05	0.05	0.05	0.05	0.05	0.1	0.15	0.15	0.2	0.2	0.25	0.2	0.15	0.1
EV CHARGE	**38**	5	5	5	5	5	5	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
EV DISCHARGE	**-18**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-3.6	-3.6	-3.6	-3.6	-3.6	0
SOLAR PV	**-31.5**	0	0	0	0	0	0	0	0	0	-2.25	-4.5	-4.5	-4.5	-4.5	-4.5	-4.5	-2.25	0	0	0	0	0	0	0
Driving (km)	**100**	0	0	0	0	0	0	0	0	50	0	0	0	0	0	0	0	0	50	0	0	0	0	0	0
EVSoC (%)		55%	63%	71%	79%	87%	95%	100%	100%	84%	84%	84%	84%	84%	84%	84%	84%	84%	68%	62%	56%	50%	45%	39%	47%

Figure 16 - Scenario 1 target profile (model).



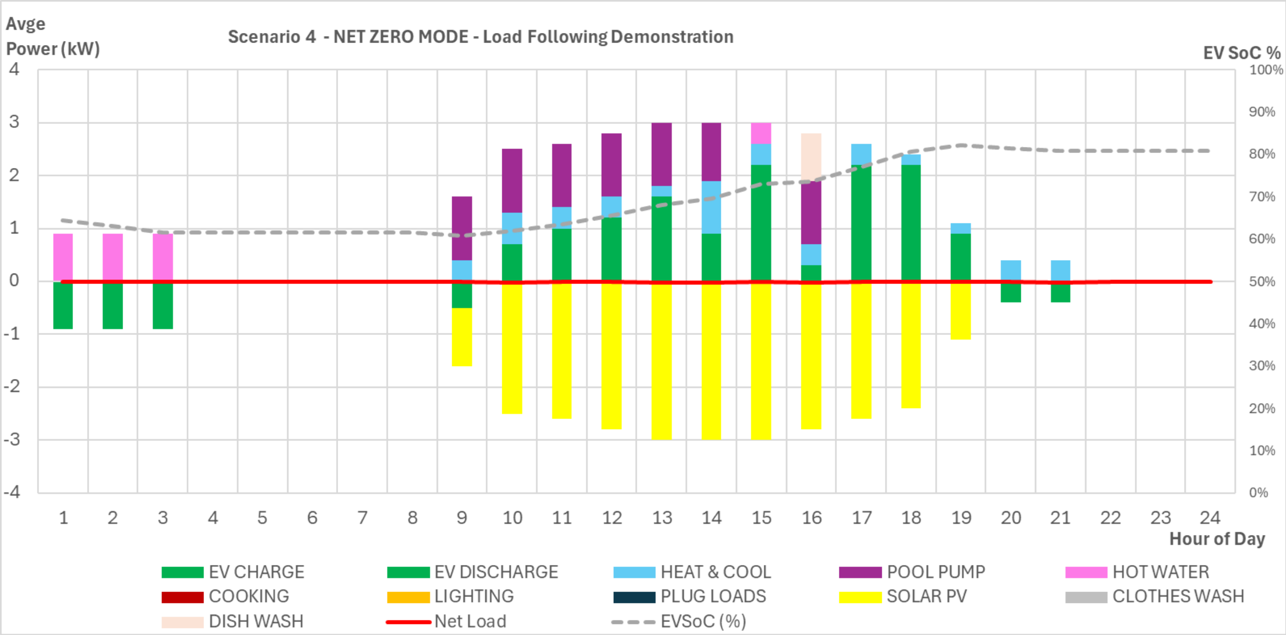
Hour	TOT (kWh)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Net Load	**1.89**	1.85	1.85	1.85	1.05	1.05	1.05	2.45	1.95	1.15	-1.67	0.91	0.85	0.55	0.8	0.55	0.8	-0.1	-3	-2.35	-2.6	-2.55	-2.3	-2.35	0.1
HEAT & COOL	**7.14**	0	0	0	0	0	0	1.2	0.6	0.6	0.48	0.36	0.3	0	0	0	0	0	0	0.6	0.6	0.6	0.9	0.9	0
HOT WATER	**2.4**	0.8	0.8	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
COOKING	**1**	0	0	0	0	0	0	0	0	0.25	0	0	0	0	0.25	0	0	0	0.25	0.25	0	0	0	0	0
CLOTHES WASH	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
DISH WASH	**1.2**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.2	0	0	0	0	0	0	0	0
POOL PUMP	**8**	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LIGHTING	**1.8**	0	0	0	0	0	0	0.2	0.2	0.2	0	0	0	0	0	0	0	0	0.2	0.2	0.2	0.2	0.2	0.2	0
PLUG LOADS	**2.45**	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.15	0.1	0.1	0.05	0.05	0.05	0.05	0.05	0.1	0.15	0.15	0.2	0.2	0.25	0.2	0.15	0.1
EV CHARGE	**30**	0	0	0	0	0	0	0	0	0	0	5	5	5	5	5	3	2	0	0	0	0	0	0	0
EV DISCHARGE	**-21.6**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-3.6	-3.6	-3.6	-3.6	-3.6	-3.6	0
SOLAR PV	**-31.5**	0	0	0	0	0	0	0	0	0	-2.25	-4.5	-4.5	-4.5	-4.5	-4.5	-4.5	-2.25	0	0	0	0	0	0	0
Driving (km)	**40**	0	0	0	0	0	0	0	0	0	20	0	0	0	0	0	20	0	0	0	0	0	0	0	0
EVSoC (%)		65%	65%	65%	65%	65%	65%	65%	65%	65%	58%	66%	74%	82%	90%	98%	97%	100%	94%	88%	83%	77%	71%	65%	65%

Figure 17 - Scenario 2 target profile (model).



PROFILE PLOT																									
Hour	TOT (kWh)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Net Load	**-7.995**	0.85	0.85	0.85	0.05	0.05	0.05	-0.8	-2.2	-0.93	-2.35	2.15	2.15	1.55	2.4	2.45	-0.6	2.6	-3.75	-1.75	-2.6	-2.85	-3.02	-3.25	0.1
HEAT & COOL	**9.18**	0	0	0	0	0	0	0.3	0.6	0.9	0.6	0.6	0.6	0	0.6	0.9	0.6	0.6	0.6	1.2	0.6	0.3	0.18	0	0
HOT WATER	**2.4**	0.8	0.8	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
COOKING	**1**	0	0	0	0	0	0	0	0	0.25	0	0	0	0	0.25	0	0	0	0.25	0.25	0	0	0	0	0
CLOTHES WASH	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
DISH WASH	**1.2**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.2	0	0	0	0	0	0	0	0
POOL PUMP	**8**	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
LIGHTING	**1.8**	0	0	0	0	0	0	0.2	0.2	0.2	0	0	0	0	0	0	0	0	0.2	0.2	0.2	0.2	0.2	0.2	0
PLUG LOADS	**2.45**	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.15	0.1	0.1	0.05	0.05	0.05	0.05	0.05	0.1	0.15	0.15	0.2	0.2	0.25	0.2	0.15	0.1
EV CHARGE	**30**	0	0	0	0	0	0	0	0	0	0	5	5	5	5	5	0	5	0	0	0	0	0	0	0
EV DISCHARGE	**-21.6**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-3.6	-3.6	-3.6	-3.6	-3.6	-3.6	0
SOLAR PV	**-43.425**	0	0	0	0	0	0	-1.35	-3.15	-3.38	-4.05	-4.5	-4.5	-4.5	-4.5	-4.5	-4.5	-3.15	-1.35	0	0	0	0	0	0
Driving (km)	**40**	0	0	0	0	0	0	0	0	20	0	0	0	0	0	0	20	0	0	0	0	0	0	0	0
EVSoC (%)		55%	55%	55%	55%	55%	55%	55%	55%	48%	48%	56%	65%	73%	81%	89%	82%	90%	85%	79%	73%	67%	61%	55%	55%

Figure 18 - Scenario 3 target profile (model).



PROFILE PLOT																										
Hour	TOT (kWh)		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Net Load	0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
HEAT & COOL	5.4		0	0	0	0	0	0	0	0	0.4	0.6	0.4	0.4	0.2	1	0.4	0.4	0.4	0.2	0.2	0.4	0.4	0	0	0
HOT WATER	3.1		0.9	0.9	0.9	0	0	0	0	0	0	0	0	0	0	0	0.4	0	0	0	0	0	0	0	0	0
COOKING	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CLOTHES WASH	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DISH WASH	0.9		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.9	0	0	0	0	0	0	0	0
POOL PUMP	8.3		0	0	0	0	0	0	0	0	1.2	1.2	1.2	1.2	1.2	1.1	0	1.2	0	0	0	0	0	0	0	0
LIGHTING	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PLUG LOADS	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EV CHARGE	13.2		0	0	0	0	0	0	0	0	0	0.7	1	1.2	1.6	0.9	2.2	0.3	2.2	2.2	0.9	0	0	0	0	0
EV DISCHARGE	-4		-0.9	-0.9	-0.9	0	0	0	0	0	-0.5	0	0	0	0	0	0	0	0	0	0	-0.4	-0.4	0	0	0
SOLAR PV	-26.9		0	0	0	0	0	0	0	0	-1.1	-2.5	-2.6	-2.8	-3	-3	-3	-2.8	-2.6	-2.4	-1.1	0	0	0	0	0
Driving (km)	0		0	0	0	0	0	0	0	0	0	-0	0	0	-0	-0	0	-0	0	0	0	0	-0	0	0	0
EVSoC (%)			65%	63%	62%	62%	62%	62%	62%	62%	61%	62%	64%	65%	68%	70%	73%	74%	77%	81%	82%	81%	81%	81%	81%	81%

Figure 19 – Scenario 4 target profile.

7 V2G Laboratory Simulation Results

7.1 Introduction

The pilot study implemented Scenarios 2, 3 and 4 due to their feasibility to be run within the available testing window. This approach enabled fast-tracked development and debugging of prototype automation and data acquisition systems while still providing valuable insights into the issues around V2G integration performance. Scenario 1 was prioritised lower due to vehicle availability constraints and will be undertaken in Phase 2.

A structured test schedule replicated the target load profiles for Scenarios 2, 3 and 4, aiming to achieve a reasonably accurate representation over 24 hours of the target load profiles. Six tests were conducted on six separate days, with appliances monitored individually or grouped based on metering capabilities.

The six 24-hour tests were run as follows.

SCENARIO 2: Winter Climate

- TEST 1: 28 October 2024; TEST 2: 29 October 2024

SCENARIO 3: Spring Climate

- TEST 3: 30 October 2024; TEST 4: 31 October 2024; TEST 5: 06 November 2024

SCENARIO 4: Load Following

- TEST 6: 13 March 2025

The detailed appliance scheduling for each scenario is provided in the Appendix in Section 11.

As described earlier, all the large appliance loads were metered on separate circuits, and the smaller loads (cooking, lighting and clothes washing) were combined onto a single circuit. Not all appliances in the prototype facility currently have automatic switching capability, for example, the washing machine was controlled manually during the tests.

Simulation of the heating and cooling load was controlled by choosing a target set point on the “internal” A/C unit installed in the simulator to represent the house A/C. The external climate around a shipping container that houses the simulator is controlled by a separate “external” A/C unit which is used to approximate the external climate conditions. By adjusting the “external” climate, the load profile for the internal A/C unit can be adjusted to approximately match the required target profile for a specific season’s heating and cooling load predicted in the modelled house.

To create the driving load on the EV battery, the EV was disconnected from the simulator and physically driven for 20km at 9 AM and 3 PM as per the test schedule.

Results from the six days of laboratory simulations under the two scenarios modelled are outlined in the following sections.

7.2 Scenario 2 Tests

The V2G laboratory successfully simulated the target load profiles for Scenario 2 using the CHAdeMO V2G setup. Key observations include:

- **Solar PV Generation Variability**: Two days of testing were actually run in spring, rather than winter as was assumed in the model, so the solar generation was larger than predicted during the test.
- **Simulating Climate:** We were able to adequately simulate the modelled winter heating and cooling load, demonstrating that we could simulate heating and cooling loads for winter even with the actual spring climate at the time of the laboratory testing.
- **Load Profile Accuracy**: Appliance energy consumption closely matched modelled values, with minor variations attributed to real-world weather fluctuations.

Figure 20 illustrates test results for Scenario 2 - Test 1, including appliance loads and vehicle state-of-charge (SoC), while Figure 21 - Scenario 2 comparison of target and experimental load profiles (no solar). compares model target and experimentally measured load profiles for both days of Scenario 2 testing. Further results are provided in the Appendix. Overall, the Scenario 2 tests demonstrated the laboratory's ability to replicate realistic EV, household and appliance energy profiles.

7.3 Scenario 3 Tests

Scenario 3 tests were conducted using CHAdeMO V2G based on spring climate conditions with daytime EV charging and pool pump usage. Key observations for these tests include:

- **Weather Impact**: Cloudy conditions reduced solar generation compared to modelled predictions.
- **Equipment Performance**: On the second day of testing, the Quasar Wallbox charger failed to discharge as scheduled, for an unknown reason.

The 24hr load profile measured during Scenario 3 - Test 3, along with EV battery SoC are shown in Figure 22. Target load profiles for Scenario 3 along with the simulated load profiles and EV SoC profile generated in the tests for all three days of Scenario 3 testing are shown in Figure 23. Further results for Scenario 3 are shown in the Appendix. Again, equipment failures aside, these results show that the laboratory simulator effectively replicated the target modelled load profiles for Scenario 3.

7.4 Scenario 4 Test

A single Scenario 4 test was conducted using the CCS2 bidirectional charging setup in mild Autumn climate conditions with daytime EV charging and pool pump usage utilising solar generation. Although this setup is capable of controlling significant grid export, a simplified load profile was used for this test as an initial demonstration of the load following capability facilitating solar self-consumption. Key observations include:

- **Reduced Appliances**: A simplified test was run for Scenario 4 with no cooking, clothes washing or lighting loads.
- **Weather Impact**: Cloudy conditions reduced solar generation compared to modelled predictions and resulted in solar variability which provided a good test for the load following capability of the CCS2 charger.

The load profile measured during the Scenario 4 test along with EV battery SoC is shown in Figure 24. Target load profile (net-zero) and the experimentally measured load profile are compared in Figure 25. The results show that the CCS2 bidirectional setup, was able to successfully follow a simple load curve, switching between charging and discharging as required. The resulting net-load profile was close to net-zero, facilitating solar self-consumption with negligible grid import or export. The household loads were not large for this initial demonstration and as such the EV was only discharged at low power (<1.5kW) during the test.

SCENARIO 2: Winter Climate, Overnight Pool Pump

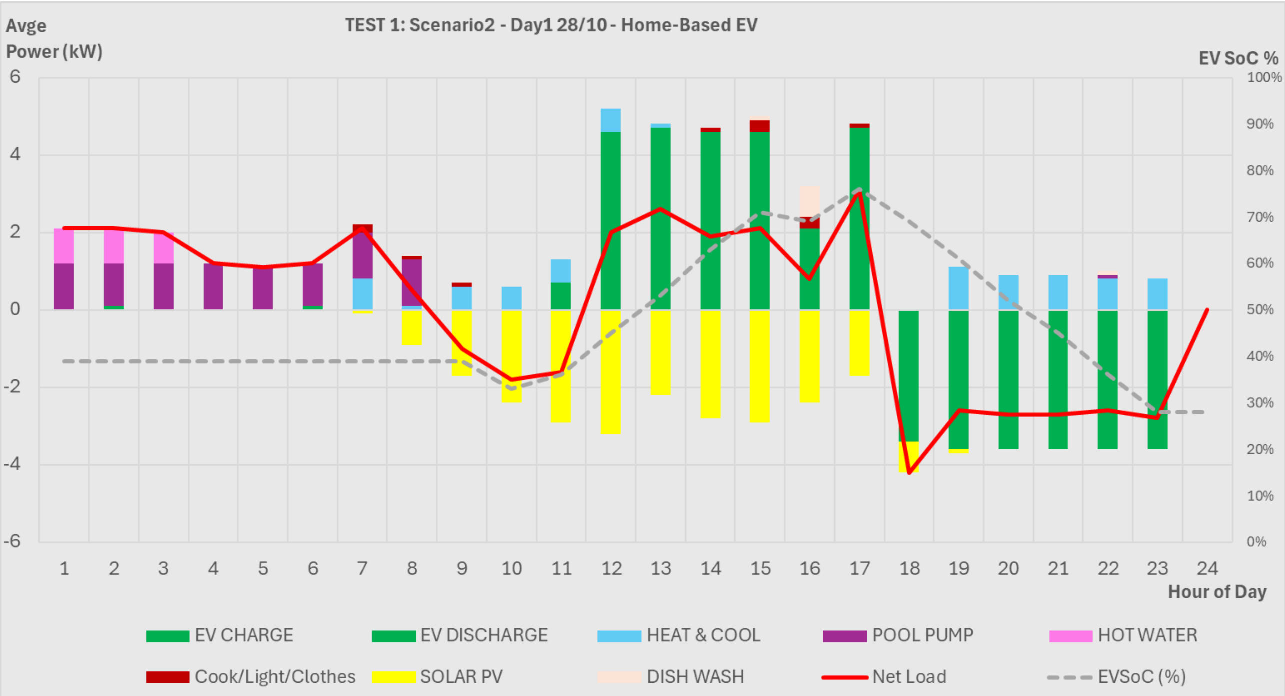


Figure 20 – TEST 1: Scenario 2 laboratory simulation.

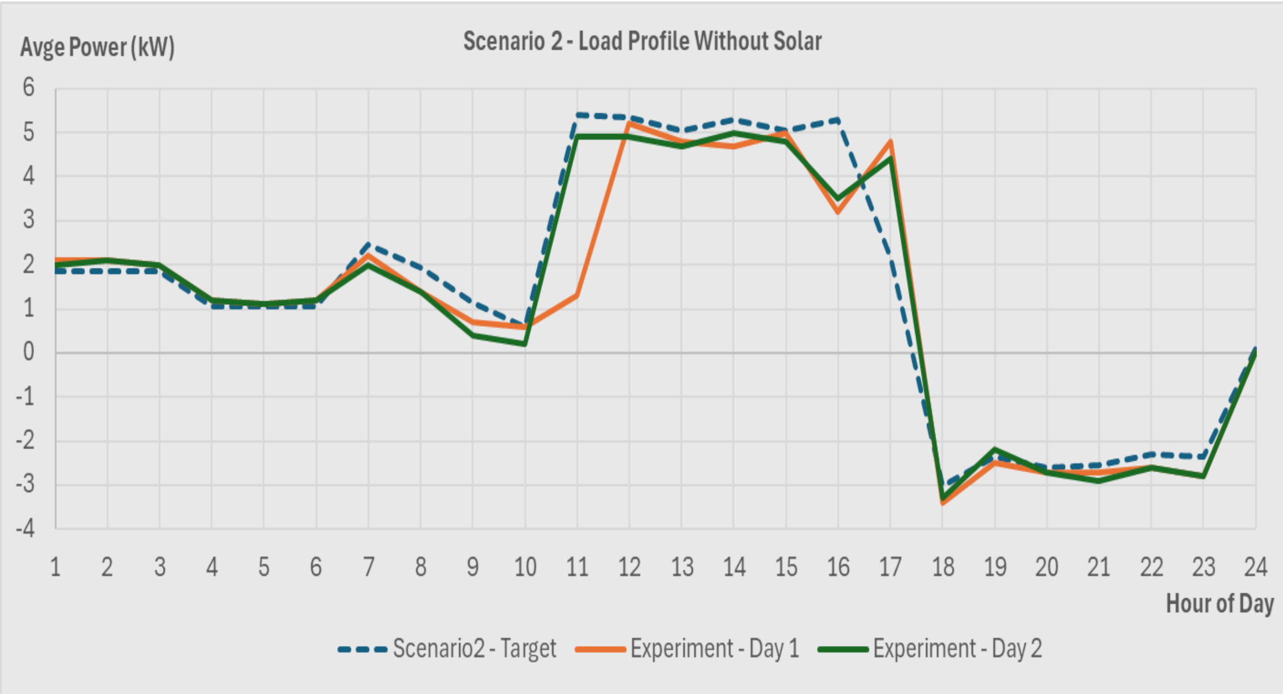


Figure 21 - Scenario 2 comparison of target and experimental load profiles (no solar).

SCENARIO 3: Spring Climate, Daytime Pool Pump

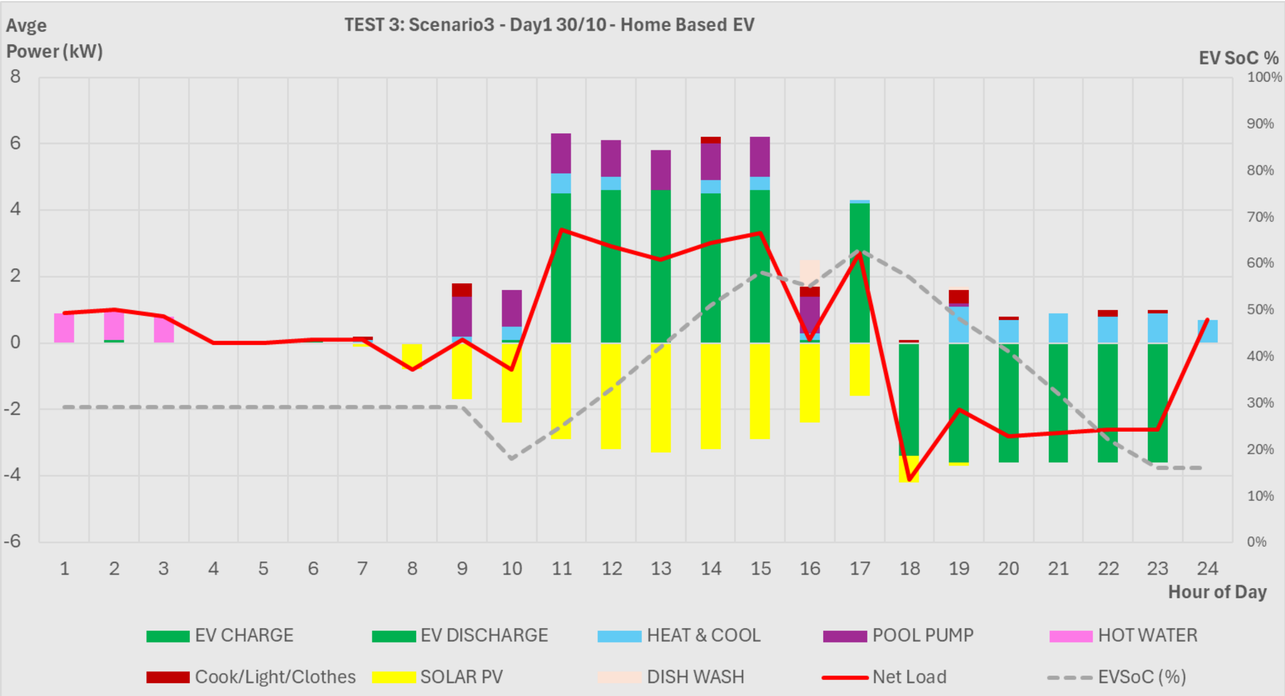


Figure 22 – TEST 3: Scenario 3 laboratory simulation.

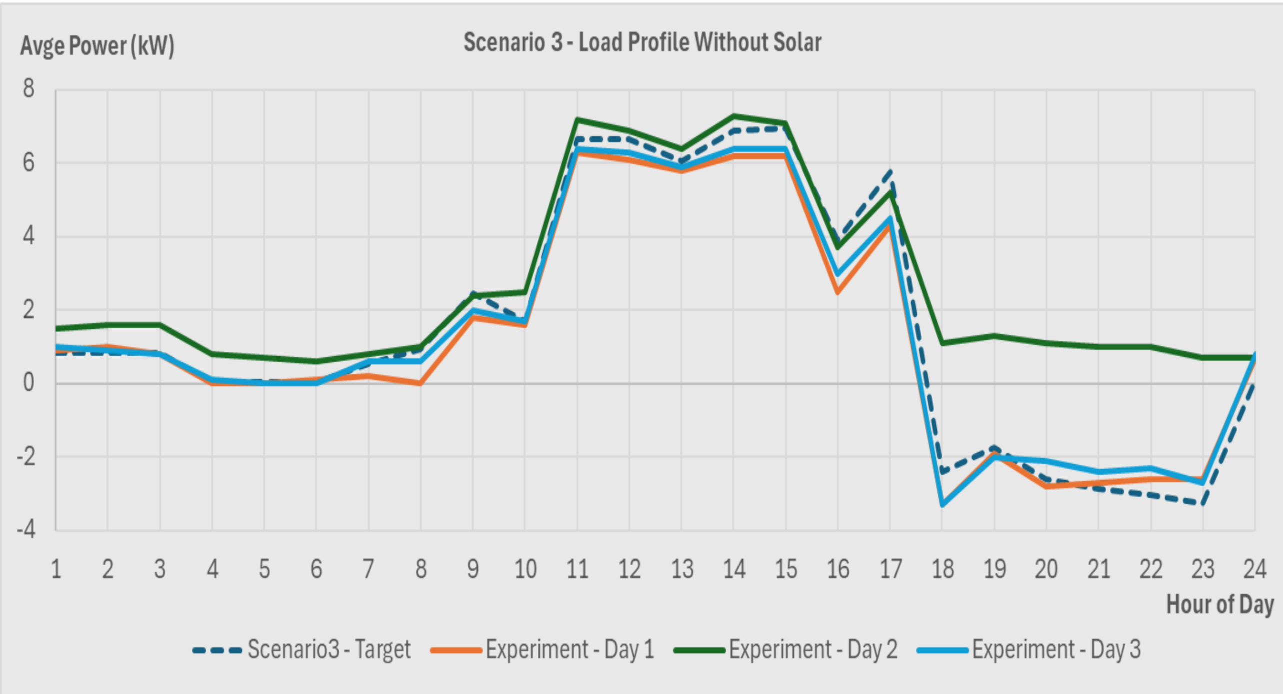


Figure 23 - Scenario 3 comparison of target and experimental load profiles (no solar).

SCENARIO 4: Autumn Climate, Load Following

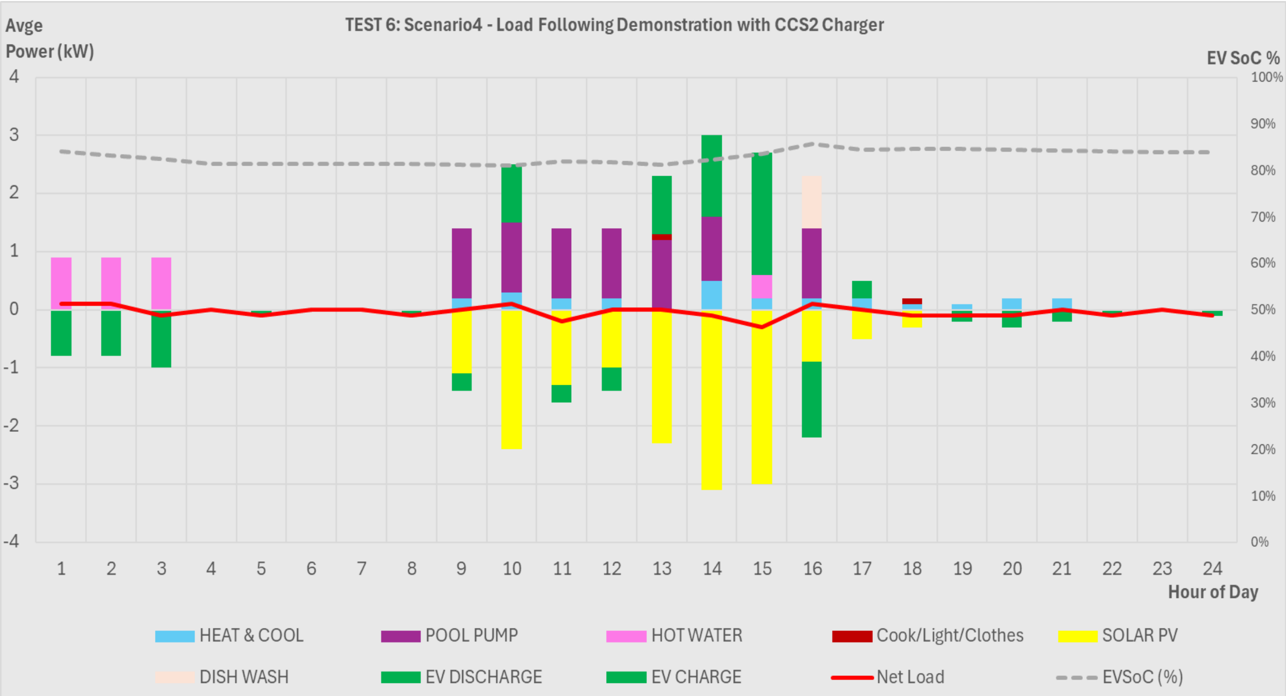


Figure 24 – TEST 6: Scenario 4 demonstration of load-following with using CCS2 charger.

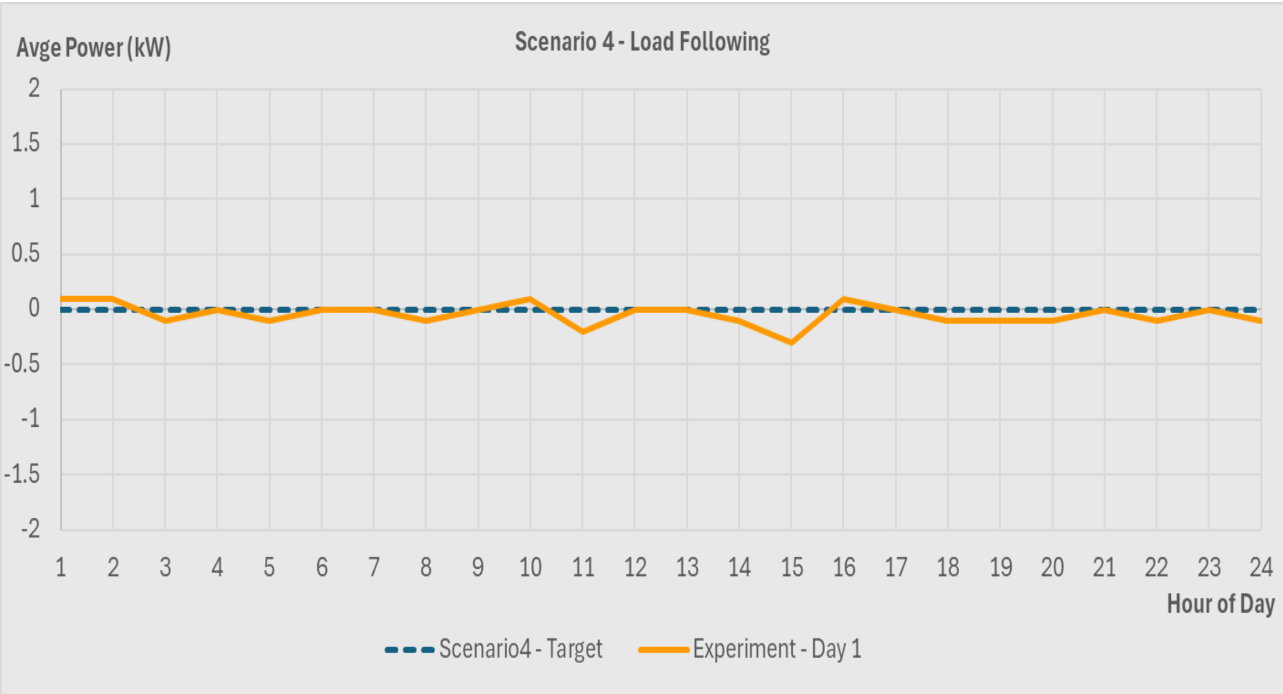


Figure 25 - Scenario 4 comparison of target and experimental load profiles.

7.5 EV charge, discharge and driving

The Nissan Leaf's state-of-charge (SoC) data as captured throughout the first five experiments is presented in Figure 26. Analysis of this data shows:

- **Consistent Performance**: Charging and discharging rates remained stable, with slightly smoother charge cycles when compared to discharge cycles.
- **Driving Impact**: SoC reductions are evident during 20km driving events at 9 AM and 3 PM. These were reasonably consistent, with some minor variability attributed to driving style, route and weather conditions.
- **Anomalies**: A discharge failure occurred during one test (31 Oct).

The SoC data was captured automatically from the EVSE when the vehicle was plugged in, at variable time intervals - depending on the rate-of-change of the SoC. Battery SoC was also recorded manually when the vehicle was not plugged in just before and after driving events.

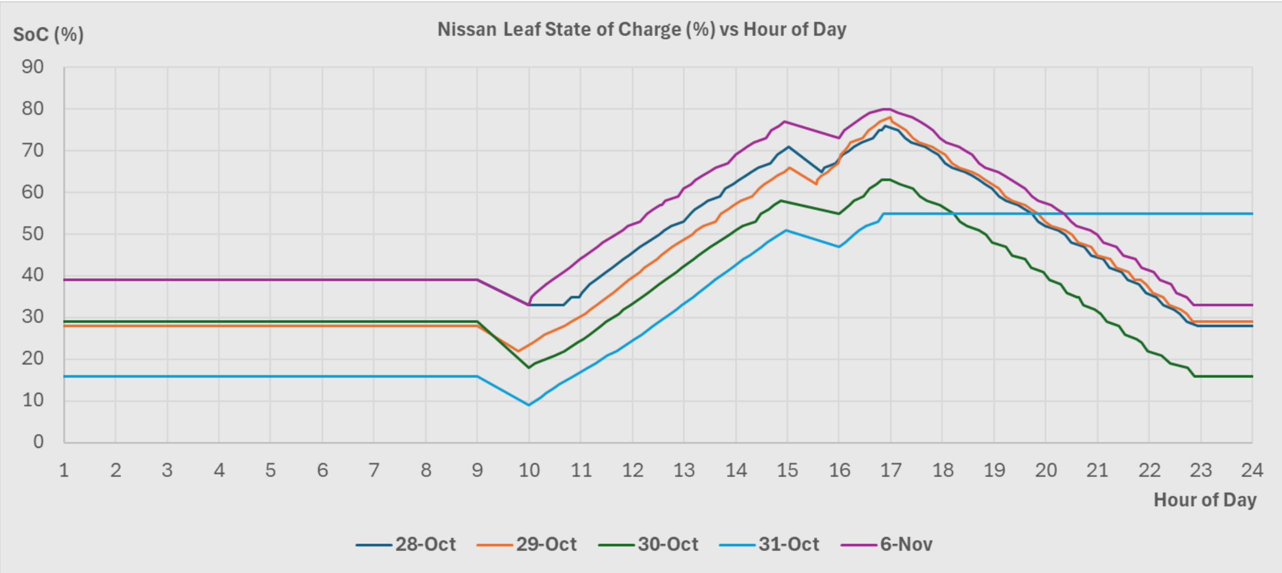


Figure 26 - Nissan Leaf state-of-charge during experiments.

7.6 Discussion

The pilot phase successfully validated the V2G laboratory's ability to simulate realistic household energy profiles and to integrate currently available and soon to be released V2G technologies for 2 different plug types. Key achievements of the pilot study include:

1. Accurate replication of household load profiles.
2. Demonstrated integration of both CHAdeMO and CCS2 EVs and bidirectional charging systems for automated self-consumption and grid export of excess generation from a combination of solar PV and discharging of the EV. The CCS2 bidirectional charging system demonstrated the ability to follow a simple load curve and run in net-zero mode with minimal import or export from/to the grid.
3. Future laboratory development. The CHAdeMO V2G setup with Nissan Leaf EV and Wallbox Quasar will eventually become obsolete when a broader range of new vehicles and EVSEs with CCS2 and updated ISO 15118 bidirectional charging capability come onto the market [11] [12]. The V2G laboratory can be updated accordingly as these new technologies becomes available. Future infrastructure improvements for the laboratory that have been identified and proposed include:

Data Integration: Standardise data formats and refine data acquisition systems for seamless assimilation and visualisation of captured data. This will enhance the accuracy and efficiency of data analysis.

Automation: Fully automate appliance scheduling and control to eliminate the need for manual interventions. Whilst there was minimal manual intervention during the 5-day intensive test run, the team did find further opportunities for automation. This will improve the reliability and consistency of the experimental simulations and also ensure repeatability.

Expand Range of Appliances: Incorporate additional appliances that reflect a wider range of modern all-electric household configurations. This will provide a more comprehensive understanding of household energy dynamics. Key items to consider include heat pump water heater and HVAC systems. Further expansion could consider controllable fans and alternative forms of thermal batteries such as pool heaters. Simulation of cooking loads is also recommended with a WI-FI enabled induction cooktop and oven.

Enhanced Load Metering and Control: Develop a metering schema which enables independent simulation and metering of all minor household loads, such as lighting, cooking, and washing machines. This will ensure a more complete and detailed energy profile. Incorporate capability to manage household loads based on telemetry data and constraints such as production or price targets.

Charger Control: Implement more advanced control-loop functionality for EV charge and discharge variations based on real-time household energy flows, telemetry data, operating conditions and artificial intelligence (AI). This will enable simulation of intelligent energy management for the home - including more advanced capability with optimised load-following or grid-export discharge behaviour. This potentially provides Essential Energy with the technical knowledge to deploy EVs to outage areas as mobile generators.

Discharge instead of driving: Implement a system to simulate different driving patterns on the vehicle by automatically discharging EV battery to a set level in place of physically driving the vehicle. This will streamline the testing process, especially for longer test runs over multiple days.

New Scenarios: Develop and run new household scenarios and configurations to test enhanced laboratory capabilities. This will expand the range of use-cases and improve the robustness of the findings.

Gateway Devices: Gateway devices offer opportunities to control older assets and enable control over assets that have no native smart capability. The laboratory currently has several appliances with gateway-style connectivity, such a pool pump and a resistive hot water system. It also has older inverters with a gateway present, allowing unique integration testing opportunities.

Premises-level export and import management: Develop capability to manage multiple household DER assets simultaneously including fixed batteries. The future home is likely to have several devices capable of exporting to the grid and equally importing from the grid at a level unsustainable for the network without a level of management. A typical use-case is for premises with older 6mm (40A, 9kW) electricity supply services. In these instances, a 7kW AC charging session and nominal household loads could potentially overload the service. Equally, multiple devices exporting, such as solar and a V2G EV could exceed export limits and asset ratings.

Extended abnormal network simulation capability: Incorporate capability to test in abnormal network conditions including voltage and frequency excursions. Frequency shifting is emerging as a critical capability for microgrid solar inverter backstops. The impact on frequency shifting with V2G is a completely unexplored area and may have significant implications for system support in contingency events if frequency shifting affects V2G capability. capability.

8 EV Battery Health Testing

8.1 Introduction

EV driving patterns/styles and amount of DC fast-charging are by far the two largest factors that impact EV battery life. However, EV battery health is still a critical consideration in V2G systems, given the possible restrictions around Original Equipment Manufacturer (OEM) warranty conditions, and consumer concerns around how frequent charging and discharging impacts the long-term performance of the vehicle's battery. During the pilot phase of the project, we have established some baseline battery health metrics which can be used to assess the impacts of V2G operation on battery health over the next phase of the project.

8.2 Results

Battery health measurements for the Nissan Leaf were taken at the beginning of the pilot project and are shown in Figure 27. The battery health testing for the pilot phase is quite rudimentary and looks purely at cell voltages across the Nissan Leaf Battery Pack. The voltages were measured immediately after a very slow charge up to full. These results can be used as a benchmark for further testing in Phase 2 after more intensive V2G cycling of the battery.

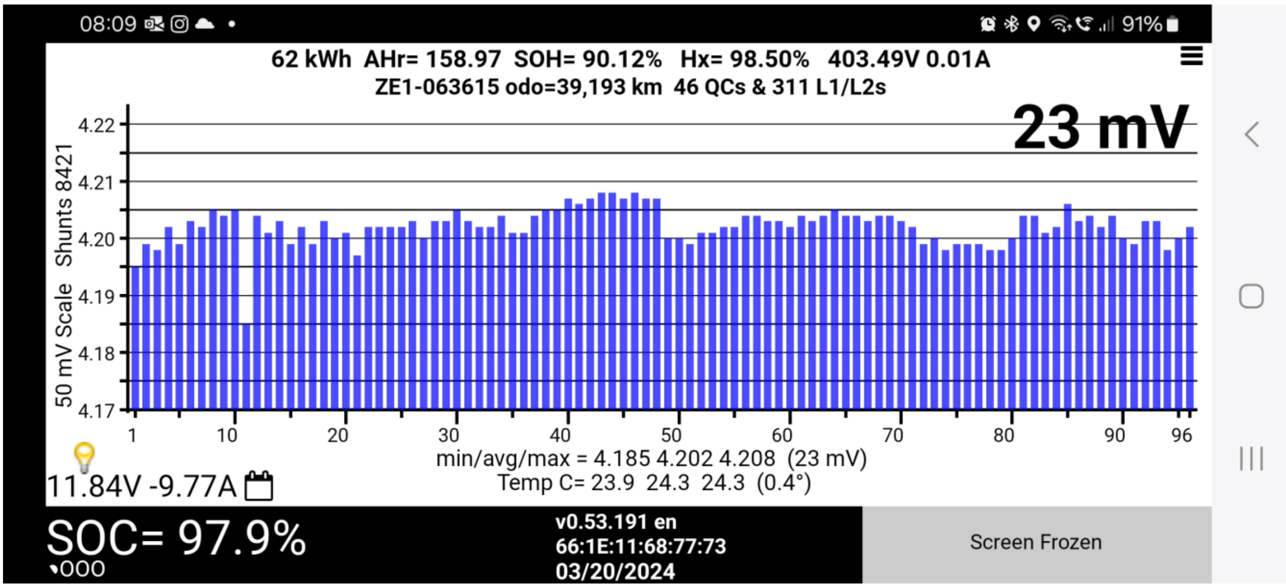


Figure 27 - Nissan Leaf battery fingerprint.

9 Summary of Key Findings

The pilot demonstration phase of the V2G Pilot Project has developed a simulator that can be used to test the feasibility and potential benefits of integrating new and emerging bidirectional EV charging technologies into residential energy systems. Key findings are summarised below:

1. **Successful Simulation of Household Load Profiles**:
   - The V2G laboratory accurately replicated target household energy and appliance load profiles, capturing seasonal variations and providing realistic simulations.
   - The simulator enabled accurate emulation of winter heating loads during spring testing.
2. **Integration of V2G Technology**:
   - Both CHAdeMO and CCS2 V2G systems were successfully integrated into the household energy simulator.
   - Both systems supported self-consumption of stored EV energy and grid export of surplus energy from solar PV and EV discharge. The CCS2 system was used to demonstrate dynamic load-following to produce a net-zero load profile.
3. **EV Charging and Discharging Dynamics**:
   - SoC profiles for the Nissan Leaf showed consistent charging and discharging rates, with minor variability in driving energy usage due to external factors.
   - A single discharge failure highlighted the need for improved charger reliability.
4. **Further Development**:
   - Manual interventions were required for some appliance and vehicle simulations, and it is planned to develop more advanced automation capabilities.
   - CHAdeMO charging technology will likely be replaced with emerging CCS2 products.
   - More advanced communication standards and control technologies can be introduced for flexible and optimised real-time control of bidirectional EV charging under a variety of different approaches.
   - Detailed recommendations for further development of the V2G laboratory are provided in Section 10.

These findings underscore the laboratory's capability to support advanced energy simulations and provide a strong foundation for the next phase of the project.

10 Recommendations for Phase 2

Building on the achievements of the pilot phase, the following recommendations outline a menu of possible areas for advancing the laboratory capabilities and expanding the scope of V2G testing and laboratory capability during Phase 2 of the project.

10.1 V2G Laboratory Facility Development

To enhance V2G laboratory functionality and efficiency, the following improvements are recommended:

Data Integration: Standardise data formats and refine data acquisition systems for more seamless assimilation and visualisation of captured data.

Expand range of Appliances: Incorporate additional appliances that reflect a wider range of modern all-electric household configurations.

Minor Load Metering: For completeness, enable independent simulation and metering of all the minor household loads, such as lighting, cooking, and washing machines.

Charger Control: Implement simple control loop functionality for EV charge and discharge variations based on real-time household energy flows and operating conditions.

Automation: Fully automate appliance scheduling and control to eliminate the need for any manual interventions. Integrate with telemetry and control systems to enable full orchestration of appliance loads, EV charge/discharge and other household DERs.

Driving Simulator: Implement a discharging system to simulate virtual driving events in place of the current requirement to physically drive the vehicle.

New Scenarios: Develop and run new household scenarios and configurations to test enhanced laboratory capabilities.

10.2 Incorporation of Emerging Technologies

To future-proof the V2G laboratory and enable it to explore emerging technologies and industry trends, integration of the following emerging technologies into the laboratory capabilities is desirable:

New V2G-Compatible Electric Vehicles: Several new EVs with bidirectional capabilities are entering the market (e.g., Nissan CCS-based models from 2026, Kia EV9, Renault 5 E-Tech Electric, and Tesla vehicles with DC V2G support).

- **Recommendation**: Expand laboratory capabilities and work with OEMS to include these vehicles, ensuring compatibility testing with different bidirectional charging standards.

CCS2 (Combined Charging System Type-2): CCS2 is rapidly becoming the global standard for EV charging, supporting higher charging and discharging rates, enhanced compatibility across a broader range of EV EVSE manufacturers, and more advanced communication protocols to optimise energy management between EVs and the grid. Development of CCS2 capability at the laboratory has commenced in the pilot phase.

- **Recommendation**: Expand laboratory capabilities and work with vehicle manufacturers to include a broader range of CCS2 V2G capable vehicles and chargers as they become available.

Support for AC and DC Bidirectional Charging: AC bidirectional solutions (e.g., Renault and Polestar) can be configured to leverage onboard chargers, which can reduce system and consumer costs of V2G. DC solutions provide higher efficiency but generally require offboard power conversion.

- **Recommendation**: Include both AC and DC configurations in laboratory tests to assess their feasibility for residential and commercial applications.

ISO 15118-20: ISO 15118-20 is an international standard for communication between EVs and EVSE charging infrastructure [10]. It supports plug-and-play interoperability between EVs and EVSEs, advanced and secure bidirectional charging communication, and communication of real-time state-of-charge for optimised energy management.

- **Recommendation**: Upgrade laboratory systems to test the implementation and compatibility of ISO 15118-20 for both AC and DC bidirectional charging scenarios.

OCPP 2.1 (Open Charge Point Protocol): OCPP 2.1 [2] is a recently developed open standard for communication between charging stations and central management systems. It provides for real-time data exchange for monitoring and controlling charging sessions, dynamic load management to prevent grid overload during peak usage and potential for compatibility across multiple hardware providers, fostering interoperability, flexibility and scalability.

- **Recommendation**: Include a testing framework to evaluate the interoperability and remote management features provided by OCPP 2.1.

IEEE 2030.5 (Smart Energy Profile 2.0): IEEE 2030.5 [1] is an international protocol that facilitates secure, bidirectional communication between DERs and utilities. It provides support for advanced energy management applications, including demand response and V2G as well as dynamic operating envelopes, and real-time grid coordination to optimise resource utilisation and minimise operational costs. In Australia, energy resources are controlled by a single IEEE2030.5 client per site, and these need to be controlled by an energy management system. CSIP-AUS is the Australian specific version of IEEE2030.5

- **Recommendation**: Integrate IEEE 2030.5 as part of laboratory capabilities to ensure devices and DER produced for the global market such as EVs and EVSEs can be tested in the V2G laboratory, to explore functionality outside the CSIP-AUS parameters if needed.

CSIP-AUS (Common Smart Inverter Profile – Australia): CSIP-AUS [11] [12] defines an Australian-specific communication protocol for smart inverters based on IEEE2030.5, enabling effective integration of DERs. It is the framework for DER orchestration preferred by some Australian utilities. It facilitates communication between customer devices and grid operators, allowing for dynamic energy management. Key use-cases include flexible export limits, dynamic pricing and emergency load control for grid stability. CSIP-Aus requires that multiple generating devices be orchestrated to achieve export limits at a site level.

- **Recommendation**: Test EV and EVSE systems' compliance with CSIP-AUS to evaluate their readiness for dynamic operating environments in the Australian context. Use the V2G laboratory to investigate the advanced integration of EV chargers with other household energy systems (e.g., solar PV and batteries) in Australian households.

Open ADR: Although Open Automated Demand Response (ADR) is primarily designed for demand response, its applications in V2G may be of interest especially in the context of broader DR-type applications, including dynamic pricing and transactive energy services. It potentially provides an alternative to IEEE2030.5.

- **Recommendation**: Provide capability for Open ADR control in the laboratory to explore its use in aggregation and control of bidirectional charging.

10.3 Enhancing simulation capabilities with EV Emulation

Explore EV and EVSE emulation techniques to widen the scope of testing options. This will enable the laboratory to virtually test new EVs and other hardware before they are released in Australia and improve the flexibility of use-cases that can be explored.

- **Recommendation**: Introduce CSIRO's EV Emulator into the V2G laboratory ecosystem, to enable simulation of a wide range of EV models and charging systems, enabling a wider breadth of testing of different configurations.

10.4 Long-term testing and modelling of costs and benefits

Conduct further V2G tests and modelling around trade-offs between V2G revenue streams and battery degradation.

Test strategies to minimise battery degradation during V2G operations, such as managed charging algorithms and methods to assess the cumulative impact of V2G operations on EV battery health.

Develop models to assess the potential economic, financial, environmental and grid benefits long-term of V2G integration into residential and other settings.

10.5 Advanced Features and Use-cases

Dynamic Pricing and Energy Arbitrage: Use real-time pricing signals to optimise charging and discharging cycles for cost savings and revenue generation.

- **Recommendation**: Simulate real-time market conditions in the laboratory to test how dynamic pricing can influence V2G operations.

Load Balancing and Grid Support: Evaluate the ability of EVs to provide frequency control and load balancing during peak demand or minimum grid load conditions.

- **Recommendation**: Include simulations of extreme grid conditions to validate V2G systems' capabilities in supporting grid stability.

10.6 V2G Certification

The main pathway to V2G certification in Australia is via the Clean Energy Council (CEC) which will over time develop an approved product list of bidirectional EVSE chargers. The application process and testing requirements for CEC listing [13] include compliance with AS/NZS 4777.2:2020 [14] and other relevant International Electrochemical Commission (IEC) standards.

One possible goal of Phase 2 of the project is to build on the infrastructure that will be developed to incubate a parallel non-partisan and independent V2G certification and testing capability that opens the possibility for V2G technology development and certification of network-connected hardware for Australia. This service could potentially be incubated and tested in the V2G laboratory, starting from bidirectional charging demonstration partnerships for new bidirectional chargers, vehicles and associated technologies, and building this up to certification of fit-for-purpose operation of bidirectional charging for Australian networks.

- **Recommendation**: Develop a plan for incorporating V2G certification capability into the V2G laboratory to facilitate regulator and stakeholder buy-in and acceptance by industry nationally.

10.7 Industry Impact of Phase 2

Incorporating these technologies, analyses, capabilities and standards into the V2G laboratory as they evolve and enter the market over the next five years, will position the laboratory as a cutting-edge facility capable of supporting the needs of networks and households to integrate with V2G technology. These updates not only align with national and international trends but also ensure relevance to emerging market and energy system demands. Such enhancements will also strengthen the capability for Australia to take an international leadership role in the development of V2G and DER grid integration.

– **Recommendation**: Develop a 5-year framework for the next phase of the project incorporating a staged approach to the development of the V2G laboratory and an expanded set of experiments and demonstrations.

11 Appendix

11.1 Test Schedule Scenario 2

Table 2 - Scenario 2 test schedule

Appliance	Office A/C	Heater	Hot Water	Cooking	Lighting	Clothes Wash	Dishwasher	Pool Pump	EV Charger	EV Discharge	Solar PV	Driving
Label	SM12 A/C	SM02 GPO	SM01 Hot Water	SM05 Wash/Dry	SM05 Wash/Dry	SM05 Wash/Dry	SM07 GPO	SM04 Pool Pump	SM18 PNL13	SM18 PNL13	SM16 PNL11	
Notes			8kWh at 3.4kW	Small loads combined	Small loads combined	Small loads combined		1.1kw			Solis	
1			01:00- On 01:14- Off									
2			02:00- On 02:00- Off									
3												
4												
5												
6	06:00- On	06:00- On			06:30- On							
7		07:00- Off			07:30- Off							
8				08:00- On				08:00- Off			On	
9				09:00- Off								Drive 20km
10									10:00 Charge 20A			
11												
12	00:00- Off											
13				13:00- On 13:40- Off								
14												
15						15:00- On	1500- On					Drive 20km
16						1600- Off	1600- Off		Taper			
17				17:00- On 17:59- Off						17:00 Discharge 15A	Off	
18		1800- On		18:00- On								
19				19:00- Off	19:30- On							
20					20:30- Off							
21	21:00- On				21:30- On							
22					22:30- Off							
23	2300: Off	2300- Off								23:00- Off		
24			00:00- On 00:15- Off					00:00- On				

11.2 Test Schedule Scenario 3

Table 3 - Scenario 3 test schedule

Appliance	**Office A/C**	**Heater**	**Hot Water**	**Cooking**	**Lighting**	**Clothes Wash**	**Dishwasher**	**Pool Pump**	**EV Charger**	**EV Discharge**	**Solar PV**	**Driving**
Label	SM12 A/C	SM02 GPO	SM01 Hot Water	SM05 Wash/Dry	SM05 Wash/Dry	SM05 Wash/Dry	SM07 GPO	SM04 Pool Pump	SM18 PNL13	SM18 PNL13	SM16 PNL11	
Notes			8kWh at 3.4kW	Small loads combined	Small loads combined	Small loads combined		1.1kw			Solis	
1			01:00- On 01:14- Off									
2			02:00- On 02:00- Off									
3												
4												
5												
6	06:00 On Cool to 18 degrees				06:30- On						On	
7					07:30- Off							
8				08:00- On				08:00- On				
9				09:00- Off								Drive 20km
10									10:00 On 20A			
11												
12	12:00- Off											
13	13:00- On			13:00- On 13:40- Off								
14												
15						15:00- On	15:00 On 16:00 Off		15:00 Off			
16						16:00- Off		16:00Off	16:00 On 20A			Drive 20km
17				17:00- On 17:59- Off					17:00 Off	17:00 On 15A		
18				18:00- On							Off	
19					19:00- Off 19:30- On							
20					20:30- Off							
21					21:30- On							
22	22:00- Off				22:30- Off							
23										23:00 Off		
24			00:00- On 00:15- Off									

11.3 Test Schedule Scenario 4

Table 4 – Scenario 4 test schedule

Appliance	Office A/C	Heater	Hot Water	Cooking	Lighting	Clothes Wash	Dishwasher	Pool Pump	EV Charger	EV Discharge	Solar PV	Driving
Label	SM12 A/C	SM02 GPO	SM01 Hot Water	SM05 Wash/Dry	SM05 Wash/Dry	SM05 Wash/Dry	SM07 GPO	SM04 Pool Pump	SM18 PNL13	SM18 PNL13	SM16 PNL11	
Notes			8kWh at 3.4kW	Not Used	Not Used	Not Used		1.1kw	Load Follow	Load Follow	Solis	None
1			01:00- On 01:14- Off									
2			01:00- On 01:14- Off									
3			01:00- On 01:14- Off									
4												
5												
6												
7												
8								08:00- On			On	
9	06:00 On Cool to 18 degrees											
10												
11												
12	12:00- Off											
13	13:00- On											
14												
15							15:00 On 16:00 Off					
16								16:00Off				
17												
18											Off	
19												
20												
21												
22	22:00- Off											
23												
24			00:00- On 00:15- Off									

11.4 Additional Test Results

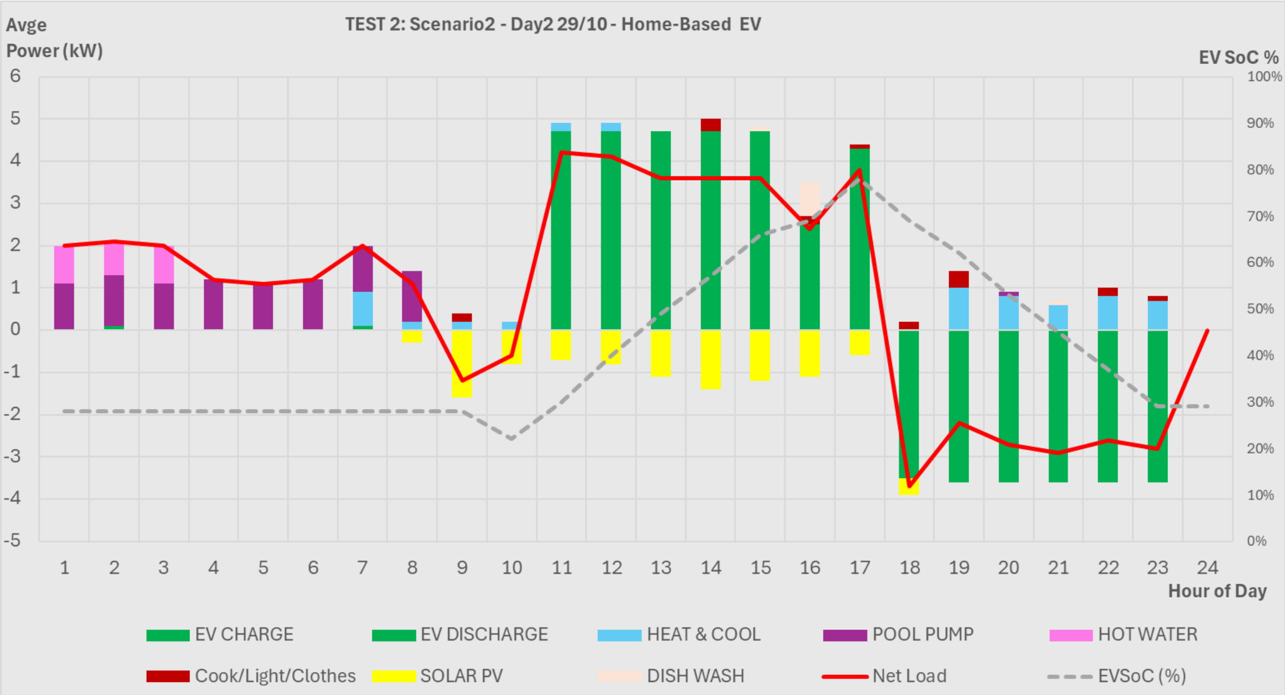


Figure 28 – TEST 2: Scenario 2 laboratory simulation.

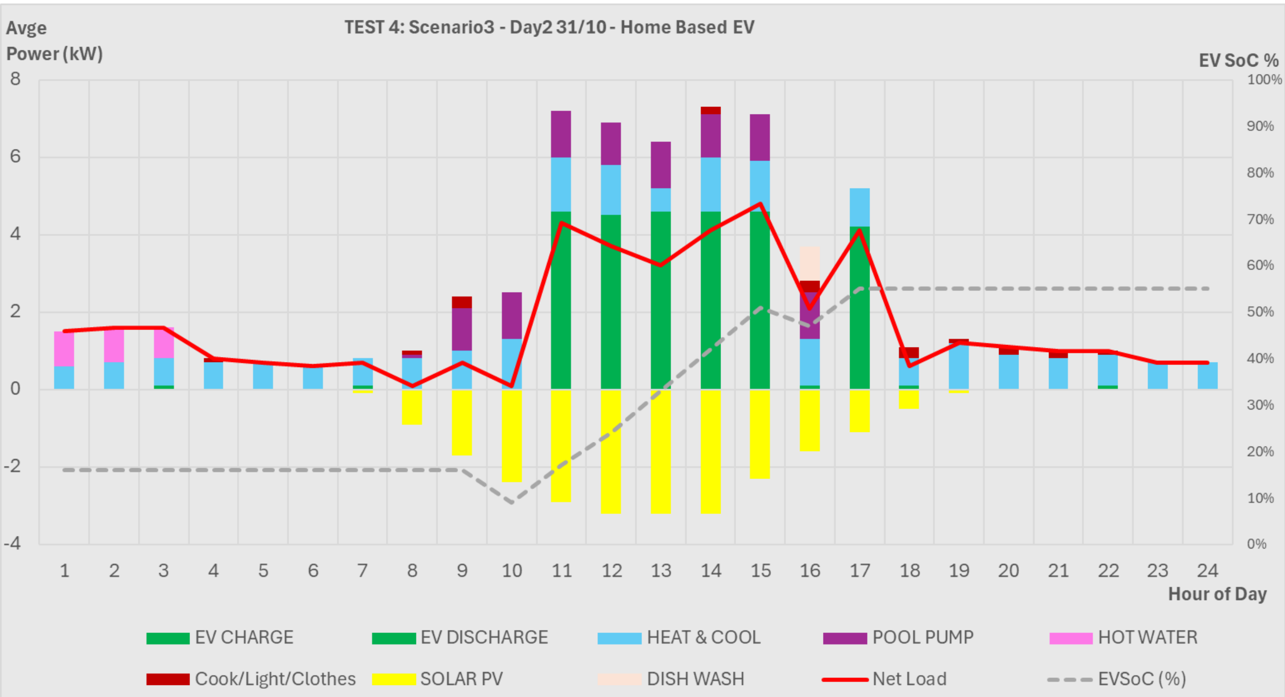


Figure 29 – TEST 4: Scenario 3 laboratory simulation.

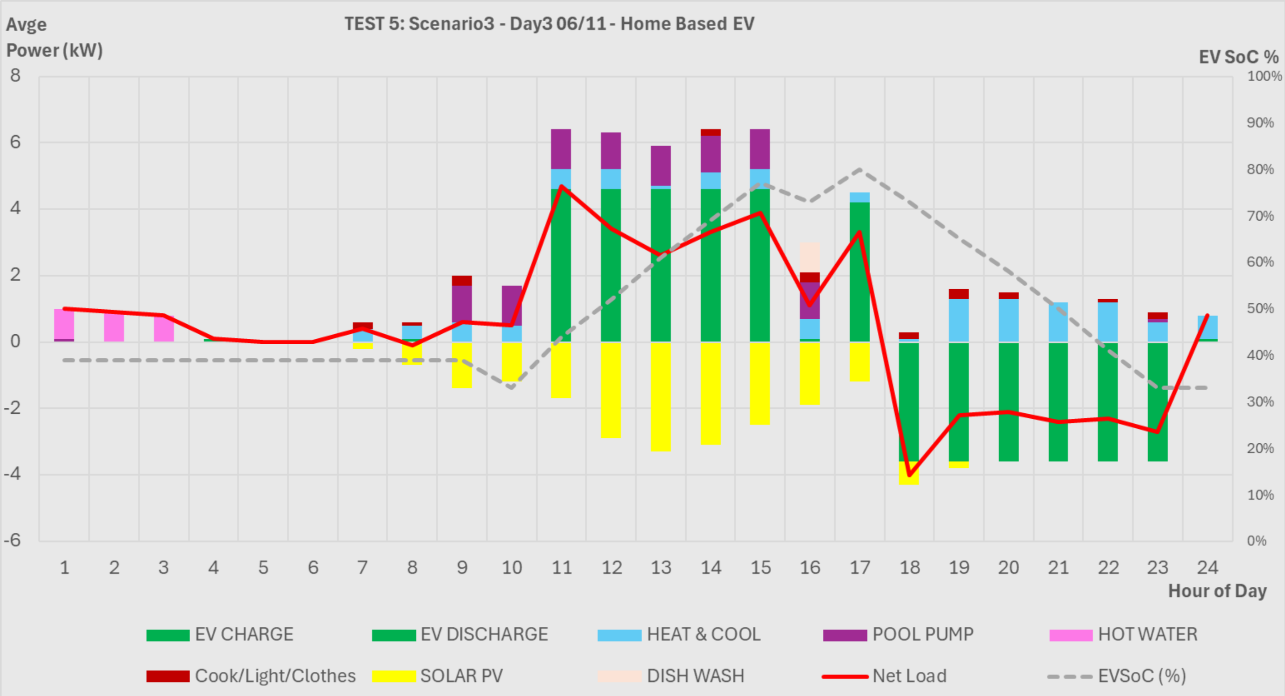


Figure 30 – TEST 5: Scenario 3 laboratory simulation.

12 Acknowledgments

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References

[1] IEEE 2030.5, 2018. [Online]. Available: https://standards.ieee.org/ieee/2030.5/5897/.

[2] OCPP 2.1, 2024. [Online]. Available: https://openchargealliance.org/protocols/open-charge-point-protocol/.

[3] O. A. Alliance. [Online]. Available: https://www.openadr.org/.

[4] Wallbox Quasar 1, 2024. [Online]. Available: https://wallbox.com/en_ca/quasar-dc-charger.

[5] Satec Australia, 2024. [Online]. Available: https://satec-global.com.au/.

[6] Home Assistant, 2024. [Online]. Available: https://www.home-assistant.io/.

[7] Home Assistant Green, 2024. [Online]. Available: https://www.home-assistant.io/green/.

[8] myWallbox, 2024. [Online]. Available: https://my.wallbox.com/login.

[9] NatHERS, 2024. [Online]. Available: https://www.nathers.gov.au/.

[10] ISO 15118-20, 2022. [Online]. Available: https://www.iso.org/standard/77845.html.

[11] CSIP-AUS, 2023. [Online]. Available: https://www.standards.org.au/blog/as-5385-2023-the-new-smart-energy-standard-supporting-australias-move-to-a-renewable-energy-future.

[12] AS 5385, 2023. [Online]. Available: https://store.standards.org.au/product/as-5385-2023.

[13] CEC Approved Solar Inverters, 2024. [Online]. Available: https://cleanenergycouncil.org.au/industry-programs/products-program/inverters.

[14] AS/NZS 4777.2:2020, 2020. [Online]. Available: https://www.standards.org.au/standards-catalogue/standard-details?designation=as-nzs-4777-2-2020.

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