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Design and implementation of a distributed energy management system for solar PV and flexible loads using a building automation platform: A residential site case study in Hamilton, Aotearoa New Zealand

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Abstract
Aotearoa New Zealand's electrification pathway increases the value of building-scale flexibility, but practical deployment depends as much on supervisory integration of onsite distributed energy resources and controllable loads, as on optimisation. Rooftop solar provides greater value when generation is used onsite rather than exported, particularly in buildings with flexible electrical loads. Using a single embedded case study design, this paper examines the design, implementation, and initial field evidence of a building automation-based distributed energy management system at a residential site in Hamilton. The analysis shows that intuitive supervisory control of distributed energy resources and controllable loads increases PV self-consumption from 12.7% under non controlled conditions to 31.3% under controlled operation, while the export share of PV generation decreases by 18.6%. Further analysis indicates that stricter control of flexible loads, such as the hot water cylinder (HWC), on a high-surplus day would reduce grid imports by 41.5%, increase site self-sufficiency from 50.6% to 71.1% in the absence of battery storage, and increase the hot-water solar fraction, defined as the share of hot-water demand met by PV, from 43.4% to 89.5%. Overall, the findings demonstrate that building-scale supervisory control of distributed energy resources can be implemented using a building automation platform and can materially increase onsite PV utilisation while reducing grid imports through coordinated control of flexible electrical loads.

Keywords: Demand flexibility; Building automation; Distributed energy management; Solar photovoltaic; Hot-water control.

1. Introduction

Electrification is central to Aotearoa New Zealand's decarbonisation pathway. It shifts energy consumption from fossil fuels towards an electricity system that is already highly renewable with the continuing expansion of renewable capacity. In 2024, 85.5% of electricity generation was renewable, with hydro and geothermal forming the backbone of supply and wind and solar growing in contribution (MBIE, 2025). Nevertheless, the operational challenge for a renewable dominant system extends beyond annual energy supply. It is shaped by coincident peak demand periods, interannual hydro variability, and the ability of the system to respond flexibly under tightening supply or network constraints.

Peak demand growth has direct cost implications because investment in generation, transmission, and distribution is driven disproportionately by relatively short periods of coincident demand. Transpower (2021) has estimated that every gigawatt of avoided peak electricity demand growth ultimately saves consumers approximately NZ$1.5 billion through avoided new generation and network upgrades and improved utilisation of existing infrastructure. Demand side measures that reduce or shift peak demand while preserving service quality and productivity are therefore of clear system value.

A recent national analysis commissioned by the Energy Efficiency and Conservation Authority (EECA) shows that Aotearoa New Zealand's flexibility potential may be larger than previously expected. EECA (2026) reports that between 1,700 and 1,900 MW of demand could be shifted away from peak periods, corresponding to around 25% of current peak electricity demand, with an implied total value of almost NZ$3 billion using Transpower's value of peak estimate. EECA's public communications further indicate that early household trials of smart control systems have demonstrated immediate efficiency gains and bill reductions in the order of 16%, highlighting that flexibility can deliver consumer level value in addition to system level benefits (EECA, 2026).

While the EECA work provides an aggregate national opportunity, this paper addresses the engineering question of how such flexibility can be delivered reliably at building-scale using cost effective monitoring and control infrastructure. Much of the identified flexibility is not located in purpose-built utility assets. It is embedded in devices already installed in homes and small- and medium-sized enterprises but seldom coordinated through a common supervisory control. The engineering question addressed here is how that flexibility can be made observable, controllable, and operationally reliable at premises-scale.

Although building scale flexibility can also contribute to peak-demand reduction, this study does not directly measure feeder level or system level peak impacts. The evidence presented here focuses instead on whether supervisory control increases onsite utilisation of rooftop PV and reduces grid imports by shifting flexible electrical demand, especially water heating, into solar rich periods.

1.1. Case study motivation

Aotearoa New Zealand's wholesale electricity market is settled using half-hour trading periods. Generators submit offers for each half-hour period, and the system operator selects the lowest-cost combination of resources to meet demand while respecting system constraints (Electricity Authority, 2025). The Electricity Authority also explains that spot prices are set every half-hour and that spot price linked retail contracts expose consumers to this volatility.

The quality and timeliness of price information have improved through the introduction of real time pricing arrangements. Prior to November 2022, spot prices were indicative and final prices were confirmed later; under real-time pricing, final spot-price information is updated at the end of each half-hour trading period, increasing price certainty for operational decisions, and supporting more responsive consumer and aggregator behaviour (Electricity Authority, 2025).

At the retail level, time varying pricing is expected to become more accessible. The Electricity Authority's 2025 reforms require large retailers to maintain or introduce compliant time varying pricing plans from 2026 onward, with guidance emphasising that these plans should reward consumption and injection patterns that reduce pressure on system costs (Electricity Authority, 2025). These developments create an enabling environment for spot price and tariff-based optimisation at a building scale, provided practical control systems can ingest price information and coordinate flexible assets safely and transparently.

Demand flexibility resources are widely distributed. For households and small- and medium enterprises (SMEs), the most scalable near term flexible assets include domestic hot water cylinders, space heating and cooling, battery storage, and EV charging. These assets are attractive because their service outputs are not tightly coupled to instantaneous electricity consumption. Hot water is a stored thermal service, space temperatures have thermal inertia, and EV charging can often be scheduled.

Aotearoa New Zealand's distribution sector has long used hot-water control for peak management, including ripple control (EECA, 2020). More recently, distribution led trials using smart metering and retailer coordination have demonstrated that residential hot water load can be moved without discernible impact on customer experience, and that such approaches can support new flexibility business models (Powerco, 2024). Peer reviewed research in the New Zealand context further supports the value of hot water cylinders as a flexibility resource by quantifying thermal storage potential and comparing alternative control strategies (Williams et al., 2024).

Electric vehicle charging is another major source of flexible demand. MBIE's analysis of smart charging identifies peak demand reduction and infrastructure deferral as core benefits and states that EECA modelling shows widespread use of smart and energy efficient EV chargers could save the country NZ$4 billion by 2050 (MBIE, 2025).

For SMEs, including schools, offices, retail buildings, and light industrial facilities, similar categories of flexibility exist, often with larger absolute loads. Heating, ventilation and air conditioning (HVAC) systems, refrigeration, water heating, and workplace EV charging can be scheduled or modulated in response to time varying prices and network constraints, subject to comfort and operational requirements. Building-scale flexibility can create value through several pathways, including coincident peak reduction, higher onsite utilisation of distributed PV, lower grid imports, and improved coordination of flexible electrical loads under service constraints.

1.2. Rationale

Despite strong national evidence of flexibility value, practical deployment at a building-scale faces persistent barriers. First, device control is fragmented. PV inverters, EV chargers, HVAC units, and hot water systems are often controlled through separate vendor specific applications, with limited coordination and ability to implement transparent, auditable optimisation logic. Second, observability and verification are limited. If flexibility is to become a dependable system resource, building-scale systems require monitoring, alarms, historical logging, and clear metrics, which are characteristic of SCADA (Supervisory Control and Data Acquisition) but not always present in consumer monitoring portals. Reviews of SCADA and Programmable Logic Controller (PLC) architectures in smart buildings indicate that SCADA principles remain relevant for reliable monitoring and supervisory control in built environments, particularly when control extends beyond a single device (OV et al., 2024). Third, cost and complexity constraint limit uptake. Utility grade SCADA and industrial Energy Management System (EMS) platforms are generally not designed for households and SMEs. In contrast, building and home automation systems are widely deployed for comfort and convenience and increasingly provide the technical primitives required for building-scale energy management: local execution, scheduling, sensor integration, actuator outputs, protocol integration, and user interfaces.

The literature recognises building EMSs as key enablers for integrating distributed generation, storage, and controllable loads, while also highlighting ongoing challenges including interoperability, security, and the gap between research optimisation methods and practical deployments (Akbulut et al., 2025; Varghese et al., 2025; Jurjević and Žakula, 2023).

1.3. Objective

The paper's main objective is to design, implement, and evaluate a building automation-based distributed energy management system that increases onsite utilisation of rooftop solar for a home with rooftop solar and flexible electrical loads in Hamilton, Aotearoa New Zealand. It seeks to:

a) Quantify PV self-consumption as the share of PV generation used onsite;
b) Quantify export share as the share of PV generation exported to the grid;
c) Quantify grid imports under observed and alternative hot-water scheduling scenarios; and
d) Check whether minimum hot water service constraints are maintained.

2. Literature review

This review examines the literature on building-scale energy management and supervisory control architectures that coordinate rooftop PV, flexible electrical loads, and market signals in residential or small-building settings. A scoping strategy was adopted because the topic spans power systems, building services, automation, control engineering, and Aotearoa New Zealand electricity policy.

Priority was given to peer reviewed studies that either report control formulations or field evidence, official Aotearoa New Zealand reports that quantify flexibility potential or describe tariff and market settings, and technical documentation only where device capabilities were necessary to explain the implemented system. Review papers were used to understand the domestic and international literature on Energy Management systems (EMS) architectures, control methods, and Heating, ventilation and air conditioning (HVAC) or demand response strategies, as well as to understand local context on electrification, pricing, and flexibility (Jurjević and Žakula, 2023; Bayasgalan et al., 2024; Akbulut et al., 2025; EECA, 2026; MBIE, 2025).

2.1. Key themes

Across the reviewed literature, six themes recur. First, the value of flexibility is driven largely by coincident peak reduction rather than by annual energy alone. Second, the most scalable building opportunities are concentrated in a relatively small set of end uses notably domestic hot water, space conditioning, battery storage, and EV charging because these loads possess thermal or electrochemical storage characteristics that allow time shifting without proportionate loss of service when properly controlled. Third, rule-based control remains attractive in field deployments because it is interpretable, robust, and light on computation, even where optimisation-based control offers higher theoretical value. Fourth, empirical multi-asset demonstrations remain rarer than simulation studies. Fifth, interoperability and cyber hygiene materially constrain real deployments. Sixth, in Aotearoa New Zealand the case for local flexibility is reinforced by quantified national potential, accelerating electrification, and the growth of time varying retail price plans (EECA, 2026; Transpower, 2020; Transpower, 2021; Concept Consulting and Retyna, 2021; Electricity Authority, 2025).

2.2. Building and home energy management systems as an integration layer

Building energy management systems (BEMS) and Home energy Management systems (HEMS) are best understood as supervisory integration layers that acquire measurements, check constraints, and issue bounded commands to existing assets. Reviews of the field consistently describe this layer as the point at which sensing, communications, control logic, user preferences, and demand-response objectives are brought together. At premises scale, the resulting functionality resembles a smallfootprint SCADA system: time stamped telemetry, historian style storage, alarms, dashboards, manual overrides, and supervisory setpoints, while native inverter, charger, thermostat, or protection functions remain authoritative (Balakrishnan and Geetha, 2021; Jurjević and Žakula, 2023; Bayasgalan et al., 2024; Akbulut et al., 2025).

This interpretation has two design consequences. First, practical performance depends as much on reliable state measurement, signal conditioning, and fallback behaviour, as on the optimisation method itself. Second, a premises EMS is constrained by heterogeneous field interfaces: relays, analogue signals, Modbus registers, proprietary APIs, and vendor-specific logic. These all must coexist within one supervisory boundary. Literature that focuses only on scheduling algorithms often treats these implementation frictions as secondary, yet fielded systems succeed or fail on precisely these details (OV GS et al., 2024; Morales-Gonzalez et al., 2024).

2.3. Control paradigms and supervisory formulations

The literature commonly distinguishes rule-based, optimisation-based, and learning-based EMS approaches. Rule-based methods dominate practical deployments because they are transparent, computationally inexpensive, and easier to commission. They are well suited to applications such as surplus-PV diversion, deadband-based hot-water control, comfort-bounded HVAC enabled logic, and deadline-aware EV charging. Recent field-oriented studies show that these simpler approaches can deliver material self-consumption or peak-management value when the flexible asset is well chosen and the operating constraints are explicit (Camblong et al., 2024; Kepplinger et al., 2024).

Optimisation-based methods remain important because they clarify the variables and constraints that any fielded controller must respect electrical balance, import and export valuation, thermal state, comfort bounds, charging deadlines, and device limits. Reviews of HEMS optimisation algorithms and recent real-time scheduling studies show a persistent trade-off between computational sophistication and deployability. The present case study therefore uses the optimisation literature less as a prescription for one universal controller than as a reference model for supervisory reasoning, while accepting that the deployed implementation includes simpler rule-based and hysteretic elements where they are operationally preferable (Varghese et al., 2025; Tifoura et al., 2025; Ali et al., 2025; Xin et al., 2024; Baumann et al., 2025).

2.4. Thermal flexibility

Domestic hot water cylinders are especially important in Aotearoa New Zealand because they combine high prevalence, material load size, and inherent thermal storage. However, not all the country's homes use electric hot-water cylinders, with alternative technologies such as gas and heat pump water heating also present in the housing stock. The applicability of hot-water based demand flexibility therefore depends on the installed water heating technology. National policy and trial literature identifies water heating as one of the most substantial residential flexibility resources, while academic studies show that stochastic draw behaviour, thermostat hysteresis, and model mismatch materially affect realised control performance. The implication is that hot water flexibility cannot be treated as an abstract energy bucket; it requires service temperature limits, realistic draw uncertainty, and conservative override logic (EECA, 2020; Powerco, 2024; Williams et al., 2024; Bishop et al., 2025; Kepplinger et al., 2024).

This literature also clarifies why domestic hot water is attractive even without batteries. The cylinder functions as low-cost thermal storage: electrical energy is shifted in time by converting surplus PV into stored heat. BRANZ and other New Zealand sources reinforce the practical significance of water-heating technology choice, control architecture, and service expectations in local housing stock (BRANZ, 2025). These findings support the Hamilton case study's implementation emphasis on tank-temperature measurement, minimum-service logic, and explicit distinction between relay-based commissioning logic and proportional immersion-heater control.

Space conditioning provides a second major flexibility resource through preheating, precooling, and setpoint adjustment. The literature consistently treats comfort as a hard or near hard constraint rather than a residual objective, especially in occupied dwellings. Predictive HVAC reviews therefore converge on the need to balance energy or price objectives against indoor thermal comfort, equipment cycling, and model uncertainty. For this reason, this case uses supervisory scheduling and bounded enable/setpoint logic rather than replacing the native HVAC control loops (Naderi et al., 2022; Xin et al., 2024; Baumann et al., 2025).

2.5. Electric vehicle charging flexibility and coordinated control

EV charging introduces a flexible load whose value is defined less by instantaneous comfort than by deadline satisfaction. The relevant question is whether the required energy has been delivered by the expected departure time. International and New Zealand work both show that unmanaged charging can exacerbate residential peaks, whereas coordinated charging can move demand into lower cost or solar rich periods. Effective integration therefore depends on an EMS that can represent charger availability, required energy by departure, site limits, and interoperability constraints rather than treating EV charging as a purely discretionary appliance load (Concept Consulting and Retyna, 2021; MBIE, 2024; MBIE, 2025; Mohseni et al., 2023).

2.6. Communication protocols, interoperability, and cybersecurity

Interoperability and cybersecurity are not peripheral concerns. Building-scale EMS deployments commonly combine Modbus, proprietary APIs, analogue signals, digital relays, and cloud-linked user interfaces across devices with different security assumptions and update cycles. Reviews of BEMS integration and building automation security show that such heterogeneity expands both engineering complexity and the cyber-physical attack surface. The controller therefore must be designed as an integration boundary with explicit assumptions about trust, access, and fallback, rather than as a frictionless software layer (Bayasgalan et al., 2024; Morales-Gonzalez et al., 2024).

2.7. Knowledge gap

The literature points to three persistent gaps. Empirical demonstrations remain fewer than optimisation and simulation studies. Tariff signals must still be translated into premises-level sensing, constraint handling, and dependable control. Many applied studies also give limited attention to interoperability, fallback behaviour, commissioning logic, and cyber security, even though these factors shape real deployments.

This study addresses a practical and analytical gap. Optimisation led case studies such as Mohseni et al. (2020) are strong on scenario analysis and planning logic, while hot-water field studies such as Kepplinger et al. (2024) provide detailed device-level evidence. Less common are residential case studies that combine supervisory architecture, mixed-interface implementation, commissioning-stage control logic, and empirical operating evidence in an Aotearoa New Zealand setting.

When commissioning logic, fallback behaviour, and measurement hierarchy are omitted, it becomes difficult to compare field studies, replicate installations, or scale successful pilots. Clear documentation of how the system was built and how the evidence was assembled is therefore part of the contribution of the study, especially in a field where the term 'EMS' covers systems ranging from simple timer-based control to multi-asset supervisory platforms.

3. Research methods

A single embedded case-study design was adopted, combined with a control-oriented engineering methodology. The case is “embedded” because one premises level energy system is examined through several linked evidence streams: installed hardware and interfaces, controller logic and commissioning behaviour, whole-site retailer data, and qualitative inverter trace evidence.

This paper reports applied research on a supervisory layer that coordinates flexible end uses and distributed generation under service constraints and market signals. The building energy system at the grid-connection boundary is the unit of analysis. Net exchange and daily account outcomes are observed directly at that boundary, whereas hot-water and HVAC behaviour are inferred from controller logic and operating signatures in the absence of continuous subsystem metering.

3.1. Case study details

The case study system includes the following equipment classes (see Tables 1 and 2):

- Photovoltaic generation and metering: a Fronius hybrid inverter and a Fronius energy meter (63A) providing PV generation and grid import/export measurement.
- Domestic hot water: a three hundred litre Rinnai hot-water cylinder with a 3-kW resistive heating element. The element is driven through an external relay/SSR stage so that the controller can use either simple on/off switching or, where required, pulse width modulation. The Loxone logic discussed later shows the supervisory on/off branch used to permit heating under PV-surplus and minimum-service conditions. Tank temperature is measured by an installed probe with a 0-10 V interface and a Pt100 sensing element.
- Space conditioning: two installed space-conditioning units (Panasonic CS-E12JKR and Mitsubishi Electric MFZ-KA50VA) coordinated at the supervisory level using two installed space-temperature sensors (one per monitored zone).
- Electric-vehicle charging: EV charging is included architecturally as a controllable load where either a smart-charger interface or a controllable charging circuit is available. The supervisory controller can support both schedule-based enable control and variable-power charging when the charger interface supports it, but separate EV field results are not reported here.

3.2. Data sources, control signals, and evidence boundary.

The supervisory controller uses three operational data classes: electrical telemetry (PV generation and point-of-connection import/export), thermal state information (hot-water cylinder temperature and indoor room temperatures), and exogenous operational information (tariff schedules, ex-post spot-price traces, calendar settings, EV departure requirements, and user-selected operating modes). For the initial field-evidence section, a fourth evidential layer is available: Genesis Energy customer-portal exports of daily net site usage and daily net billed amount from 1 August 2025 to 28 February 2026, supplemented by Fronius Solar.web production view screenshots for selected days in late February and March 2026.

Table 1. Installed hardware

Subsystem	Hardware / interface	Role	Key characteristics
Supervisory controller	Loxone Miniserver; Ethernet / Modbus TCP; analogue and relay I/O	Local EMS, telemetry, alarms, dashboards, supervisory control	19.2–30 VDC; 8 DI; 4 AI; 8 relay outputs; 100 Mbps LAN; building automation use
PV inverter	Fronius Symo GEN24 / GEN24 Plus; Modbus TCP SunSpec / JSON API	PV telemetry and future battery gateway	Wi-Fi, Ethernet, RS485, digital I/O, SunSpec, JSON API
Grid / PV meter	Fronius Smart Meter 63A-3; RS485 to inverter	Import / export metering at PCC	230–400 V; 3 × 63 A; class 1
Hot water cylinder	300 L Rinnai cylinder, 3 kW element; PWM to external SSR	Flexible thermal storage load	Duty cycle modulation: thermostat protection retained
Tank temperature sensing	Pt100 probe and PR 5114 transmitter; 0–10 V to controller	Tank thermal state input	316 SS sheath; isolated RTD transmitter
Space conditioning	Panasonic and Mitsubishi units; supervisory enabled setpoint	Flexible HVAC demand shifting	OEM protection retained; bounded supervisory logic
EV charging	Local enable or OCPP charger interface	Flexible charging	Meets departure energy target within charging window

Table 2. Commissioning chronology and evidence windows for the case study

Phase	Period	Evidence available	Interpretation
Pre-step site baseline	1 Aug–31 Oct 2025	Genesis daily net site usage and daily billed amount	Whole-site baseline showing routine daily net import before the December commissioning boundary.
Early December transition window	1–10 Dec 2025	Genesis daily net site usage and daily billed amount	Short pre-step comparison window before the December shift; treated as transitional rather than a stable baseline.
Post-step export-active window	11–31 Dec 2025	Genesis daily net site usage, billed amount, and customer-credit outcomes	Post-step window with sustained export days; reflects PV export enablement, retailer credit activation, and supervisory control.
Summer operating window	1 Jan–18 Feb 2026	Genesis daily net site usage and daily billed amount	Continued summer operation after the December transition.
Portal rows treated as missing	19–28 Feb 2026	Genesis daily rows showing 0 kWh and 0 NZD	Treated as missing data rather than true zero-energy days.
Screenshot archive	11–23 Dec 2025 and 28 Feb–13 Mar 2026	Twenty-seven Fronius Solar.web daily production-view screenshots	Used for qualitative operating-signature classification and a 15-day comparison subset.
Single-day mechanism study	13 Mar 2026	Digitised inverter day profile and reconstructed daily energy balance	Single-day allocation model showing how hot-water scheduling alters PV use, export, and grid import.

3.3. System architecture, control formulation, and evaluation framework

The architecture follows a layered hierarchy consistent with SCADA concepts applied at building scale:

- Field layer: physical devices, sensors, and actuators, including the inverter, meter, hot-water element and relay, temperature sensors, space-conditioning units, and EV charging equipment.
- Primary control layer: manufacturer-embedded controllers including inverter controls, battery-management control when present, and HVAC internal control and protections.
- Supervisory EMS and SCADA-like layer: a building-automation controller responsible for data acquisition, logging, alarms, schedules, optimisation logic, and the issuing of supervisory set-points and enable signals.
- Operator interface layer: dashboards, trends, alarms, and remote access for monitoring and manual override, with access control.

The architecture supports heterogeneous interfaces but prioritises widely deployed industrial and building integration mechanisms. Modbus TCP or Modbus RTU are used for inverter and meter data acquisition where supported, due to its prevalence in energy devices. Analogue inputs (0-10 V) are used for installed temperature-sensing signals when available. Digital outputs and analogue outputs are used to actuate relay control and provide enable or mode signals where a suitable interface exists.

For EV charging, two integration pathways are supported. The first is protocol-based control via a charger communications interface such as Open Charge Point Protocol (OCPP) when a compatible charger and backend are used. The Open Charge Alliance describes OCPP as a uniform method of communication between charge points and central systems, enabling interoperability. The second is local control through schedule based enabled signals or current limiting where supported by the charging equipment.

The building-scale SCADA-like functions implemented include:

- Real time monitoring of PV generation, grid import/export, hot water power, and indoor temperatures.
- Historical logging for energy analysis and verification.
- Alarm handling for communications failures, temperature constraint violations, abnormal grid import peaks, and device fault states where available.
- Manual override modes that allow occupants or operators to temporarily prioritise comfort or hot water recovery.
- Data availability monitoring, including heartbeat style checks for critical devices.

Building-automation security literature emphasises that legacy protocols, such as Modbus, were not originally designed with modern security primitives and that building automation systems have been targets of cyberattack, which motivates explicit segmentation and access controls when remote monitoring and control are enabled.

3.4. Control objectives

The control formulation below is used to describe the supervisory logic of the system rather than to claim that a full mathematical optimiser is solved continuously in the deployed controller. The equations provide a common reference model for the main control decisions: balancing PV generation and site demand, separating grid import from export, maintaining hot-water and comfort constraints, and scheduling flexible loads such as hot water, HVAC, and EV charging. In the implemented system, these objectives are translated into rule-based supervisory logic, including PV-surplus diversion, temperature thresholds, schedules, and service-protection overrides.

At each discrete interval t, the net grid power at the point of connection can be expressed as:

$$P_{grid,t} = P_{base,t} + P_{hw,t} + P_{HVAC,t} + P_{EV,t} + P_{batt,ch,t} - P_{PV,t} - P_{batt,dis,t} \quad (1)$$

where $P_{base,t}$ is uncontrollable building demand, $P_{hw,t}$ is hot-water electrical power, $P_{HVAC,t}$ is space-conditioning electrical power, $P_{EV,t}$ is EV charging power, $P_{PV,t}$ is PV generation, and the battery terms are included only as an optional future extension. For the presently commissioned system, the battery terms are set to zero.

Equation 1 is the site power-balance equation. It states that grid power is determined by the difference between total electrical demand and onsite PV generation. Positive grid power represents import from the grid, while negative grid power represents export. Flexible loads such as hot water, HVAC, and EV charging can therefore change the timing of grid import and export when they are scheduled to coincide with available PV generation.

Grid imports and exports are then defined as:

$$P_{imp,t} = \max\left(P_{grid,t}, 0\right), \quad P_{exp,t} = \max\left(-P_{grid,t}, 0\right) \quad (2)$$

The operational energy-cost term over a horizon H is:

$$C_{energy} = \Sigma_{t \in H}(c_{imp,t}P_{imp,t} - c_{exp,t}P_{exp,t})\Delta t \quad (3)$$

where $c_{imp,t}$ is the import price and $c_{exp,t}$ is the export remuneration. This form is compatible with fixed time-of-use schedules, spot-linked retail pass-through, or ex-post analysis using published final prices. To reflect the system value of coincident peaks, a peak penalty can be added as:

$$C_{peak} = \lambda_{peak} max_{t \in H} P_{imp,t} \quad (4)$$

Equations 2 to 4 separate the site power balance into import, export, operating cost, and an optional peak-demand term. These terms show how a supervisory controller could consider both customer-facing energy cost and system-facing peak demand. In this study, however, the measured results focus mainly on import, export, and onsite PV utilisation. The peak term is retained as part of the general supervisory framework but is not used as direct evidence of feeder-level or system-level peak reduction.

The hot-water cylinder is modelled as a thermally buffered flexible load. Its electrical input can be shifted in time because stored heat in the cylinder allows the controller to delay or advance heating while still maintaining a minimum service temperature. The thermal state of the hot-water cylinder is represented by a simplified discrete heat-balance model:

$$T_{hw,t+1} = T_{hw,t} + \frac{\left[\eta_{(hw)} P_{hw,t} - U_{(hw)}(T_{hw,t} - T_{amb,t}) - Q_{draw,t}\right]\Delta t}{C_{hw}} \quad (5)$$

with service and safety constraints:

$$T_{hw,min} \leq T_{hw,t} \leq T_{hw,max} \tag{6}$$

Because the installed cylinder uses a resistive 3 kW element switched through an external relay/SSR stage, its effective hot-water electrical power can be represented by a PWM-capable duty-cycle model:

$$P_{hw,t} = d_t P_{hw,rated}, \quad 0 \leq d\_t \leq 1 \tag{7}$$

Where d_t is the duty cycle. Equation 7 describes the actuator path when the SSR is used for proportional control. Equations 5 to 7 describe how hot-water control is represented in the supervisory framework. Equation 5 tracks the tank-temperature state, equation 6 enforces service and safety limits, and equation 7 represents the controllable electrical input to the heating element. In the field implementation, the same principle is applied through threshold-based PV-surplus logic and, where available, PWM-capable actuation. The controller therefore does not treat the hot-water cylinder as an unconstrained dump load; heating is only shifted when temperature and service constraints allow it. The commissioning-stage Loxone branch documented later is simpler: it issues a binary enable when PV-surplus and temperature conditions are satisfied. Space conditioning is represented more simply, because the EMS does not replace the native HVAC controller. Instead, the supervisory controller can enable, disable, or adjust operation within comfort limits.

$$T_{z,t+1} = a_z T_{z,t} + b_z P_{HVAC,z,t} + c_z T_{out,t} + w_{z,t} \tag{8}$$

subject to comfort bounds:

$$T_{z,min} \leq T_{z,t} \leq T_{z,max} \tag{9}$$

EV charging is treated as an energy-delivery problem with a deadline:

$$\Sigma_{t\in A} \eta_{EV} P_{EV,t} \Delta t \geq E_{req}, \quad 0 \leq P_{EV,t} \leq P_{EV,max} \tag{10}$$

Where A is the charging-availability window and E_{req} is the energy required by departure. Equations 8 to 10 represent service constraints for HVAC and EV charging. HVAC flexibility is limited by indoor comfort bounds, while EV charging flexibility is limited by the requirement to deliver enough energy before the departure deadline. These constraints explain why the controller cannot simply shift all loads to solar periods; flexibility is only useful when the required service is still delivered. A composite supervisory objective can then be written as:

$$\begin{aligned} min_u \Sigma_{t\in H} [(c_{imp,t} P_{imp,t} - c_{exp,t} P_{exp,t}) \Delta t + \lambda_{comf} \psi_t \\ + \lambda_{sw} ||u_t - u_{t-1}||] + \lambda_{peak} min_{t\in H} P_{imp,t} + \lambda_{deg} \varphi_{batt,t} \end{aligned} \tag{11}$$

Equation 11 summarises the general supervisory objective. The first term represents net energy cost after accounting for imports and exports. The comfort penalty term, ψ_t, represents violations or near-violations of temperature or service constraints. The switching penalty term discourages rapid changes in control outputs, which helps reduce control chatter and unnecessary cycling. The peak term represents the optional objective of limiting maximum grid import. The battery degradation term is included only as a future extension and is set to zero for the present installation because no battery operation is evaluated in this study.

In the deployed system, Equation 11 is not solved as a full optimisation problem at every interval. Instead, the controller implements simplified supervisory rules that approximate the same priorities: use surplus PV where possible, protect hot-water and comfort constraints, avoid unnecessary switching, and fall back to conservative operation when telemetry or external signals are unavailable.

3.5. Implemented control strategies

In this system, the control is hybrid: a generic supervisory formulation provides the analytical frame, while practical decisions are implemented through rule sets, deadbands, minimum on/off times, and explicit operator overrides. This preserves interpretability, reduces the risk of control chatter under noisy telemetry, and remains robust when some devices expose only bounded supervisory commands rather than full continuous control.

3.5.1. PV self-consumption maximisation

PV self consumption is increased by treating flexible loads as ranked sinks for otherwise-exported generation. In the implemented hierarchy, hot water is the first low risk sink when the cylinder is below its upper band and surplus PV is visible at the site boundary; EV charging is then scheduled into surplus or low-price periods when departure slack allows; HVAC preheating or precooling is used more conservatively and only when occupancy timing and comfort bands permit. The key implementation point is that surplus allocation is constrained by service protection rather than executed as a naive export elimination rule.

3.5.2. Peak shaving

Peak shaving is implemented as a supervisory import cap strategy. When measured import approaches a configurable cap, the controller reduces discretionary demand in a defined order: first hot-water heating, then EV charging, and only then comfort-flexible HVAC operation. This priority reflects service risk: brief hot-water or EV deferment is usually less intrusive than comfort violations. Minimum run-times, deadbands, and recovery logic prevent rapid oscillation and ensure that deferred loads are restored before service constraints are breached.

3.5.3. Spot price and time varying price optimisation

The supervisory controller supports a price response mode in which flexible loads are scheduled toward low-price periods and away from high-price periods. In Aotearoa New Zealand, the increasing availability of compliant time varying retail plans from 2026 onward strengthens the practical relevance of this mode, particularly for households and SMEs that cannot manually respond at half-hour granularity.

Because spot-linked retail price can include risk premiums, network charges, and retailer specific structures, the implemented method is tariff agnostic. The controller accepts a time indexed price signal whether derived from a published time-of-use schedule, a retailer tariff table, or a spot-linked series used for ex-post evaluation. In commissioning practice this mode is often heuristic rather than a continuously solved market optimiser: it shifts hot water and EV charging into low price windows while retaining hard service constraints.

3.5.4. Thermal comfort prioritisation

Space conditioning control follows a comfort first supervisory strategy. Optimisation is permitted only within predefined temperature bands and occupancy-relevant time windows. Where preheating or precooling is used, it is treated as a bounded flexibility resource rather than as an end in itself: the objective is to move some electrical demand in time without compromising the occupant experience or fighting the device's own native control loop.

Figure 2 shows that optimisation sits inside a wider supervisory stack. Telemetry, sensors, price signals, and user settings first pass through data-quality checks and constraint management before interval set-points are issued. In practice, unreliable device data requires filtering, stale-data detection, and override logic.

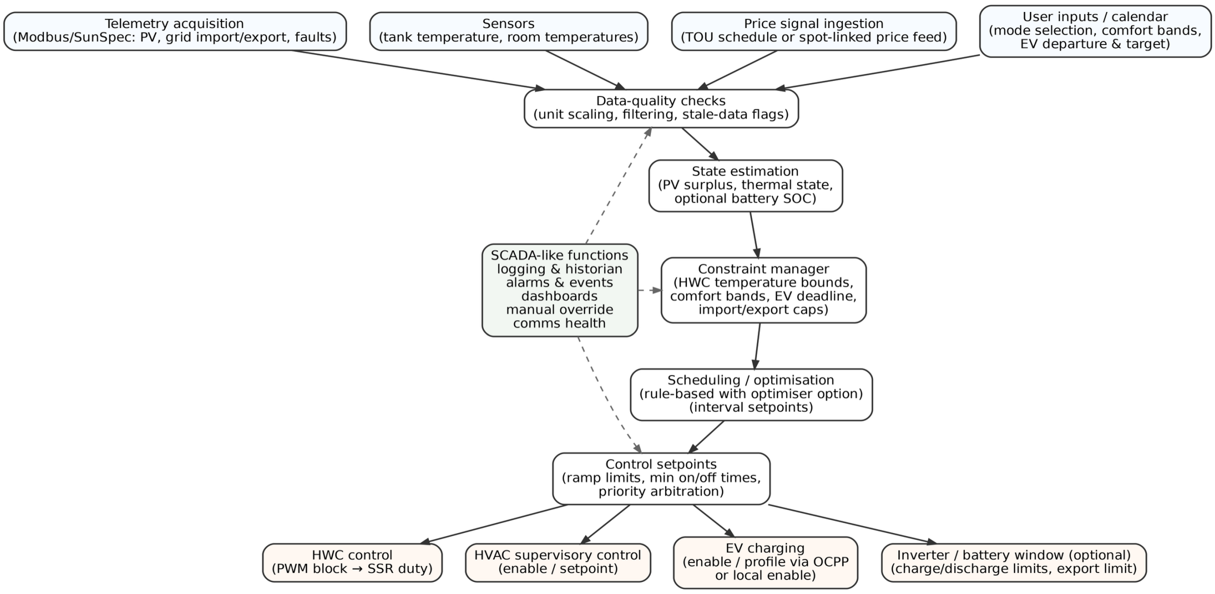

Figure 2. Supervisory data and control flow used by the EMS

The supervisory execution loop for interval scheduling is summarised in Figure 3. Forecasts, prices, and operating limits are combined in a planning stage to produce interval setpoints, which are then applied in real time through the actuator layer. Measured import/export, temperatures, and fault states are fed back to update subsequent dispatch decisions and to trigger overrides where service or safety limits are approached.

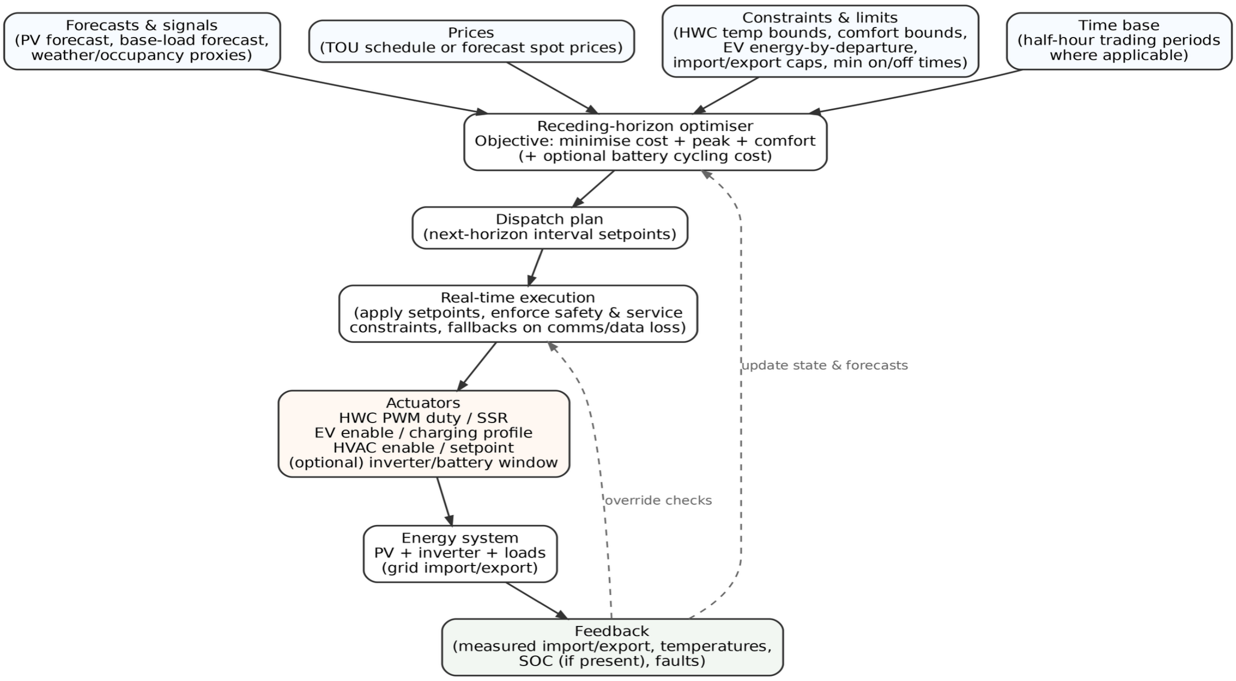

Figure 3. Receding horizon optimisation and execution loop for coordinated dispatch of PV and flexible loads

3.6. Hot-water health and safety constraints

The hot water controller maintains a conservative minimum service temperature and does not override local thermostats, thermal cut-outs, or manufacturer protections. Periodic higher-temperature operation for hygiene management remains a hard constraint rather than an optimisation objective. The EMS may choose when the element is allowed to run, but it does not displace the cylinder's safety architecture.

3.7. Evaluation framework

Table 3 summarises the intended evaluation design alongside the subset supported by available evidence. The analysis is therefore based on whole-site daily net energy exchange from retailer data and operational signatures from inverter traces and adopts a quasi before-and-after whole-site approach rather than device-level attribution.

The evaluation adopts an International Performance Measurement and Verification Protocol (IPMVP) Option C whole facility approach, consistent with the available whole-site measurements. The site meter captures aggregate outcomes, while additional submetering and device logs would be required to attribute changes to hot water, space conditioning, EV charging, and any future battery operation.

The evaluation also considers service quality, data reliability, and broader factors influencing whole-site performance. Hot-water service quality is assessed using minimum tank temperature, together with the frequency and duration of temperature constraint violations, supported by proxy indicators of unmet demand risk. Thermal comfort is evaluated as the proportion of time each monitored zone remains within the defined temperature band, along with the magnitude of any deviations. Data availability and communications performance are assessed using the proportion of expected samples successfully recorded and the occurrence of communications failures or missing data.

Whole home energy use and demand are influenced by external factors, including weather conditions, occupancy patterns, and stochastic hot-water usage. Where sufficiently detailed data are available, regression-based baseline models can be used to account for key exogenous variables such as outdoor temperature and day type. This study does not apply weather normalisation. The results are therefore presented as descriptive whole site outcomes and interpreted within the limits of the available data.

Table 3. Evaluation metrics and required data streams for a subsequent baseline-versus-controlled field study

Metric	Definition / test	Required signals	Analytical purpose
PV self-consumption	On-site PV use divided by total PV generation over the study interval	PV generation, grid export, import/export timestamps	Quantifies how much PV is retained locally rather than exported
Peak grid import	Maximum import demand over the selected interval (for example one minute or half-hour periods)	Point-of-connection power series	Assesses contribution to coincident peaks and peak-shaving value
Electricity cost outcome	Import cost minus export revenue under applicable tariff, TOU schedule, or spot-price trace	Import/export energy and tariff or price data	Measures consumer-facing economic performance of supervisory control
Hot-water service quality	Minimum tank temperature, duration and frequency of temperature-band violations, and recovery after draws	Tank temperature, duty command, draw proxy if available	Shows demand response does not compromise hot-water service
Thermal comfort	Share of time within comfort band and magnitude of deviations in each zone	Room temperatures, HVAC status, schedules or set points	Ensures comfort protection remains explicit
EV service quality	Energy delivered by departure time and any missed charging targets	Availability window, target energy, charger status or power	Protects mobility service while enabling flexible scheduling
Communications and data quality	Missing-sample rate, stale-data alarms, historian completeness, and device uptime	Heartbeat logs, historian records, alarm log	Validates supervisory reliability and dataset integrity

3.8. Reliability, resilience, and cybersecurity by design

Building automation and energy device integration raises reliability and security requirements that are often underemphasised in purely simulation-based studies. The system is designed for safe degradation. If communications with the inverter or meter fail, the system falls back to conservative schedules for hot water and EV charging. If temperature sensors fail, the system reverts to device native control behaviour.

Security controls include segmented networks for energy devices, authenticated access for remote interfaces, and minimisation of exposed services. This reflects the broader literature showing that building automation systems and protocols have well documented vulnerabilities and require compensating controls when deployed in connected environments.

3.9. Field implementation and commissioning

3.9.1. Supervisory controller and field interfaces

In this case study, a Loxone Miniserver is used as the supervisory controller. It operates on 24 VDC and provides digital and analogue inputs, relay outputs, and Ethernet connectivity supporting TCP/IP and Modbus TCP (Loxone, 2026). Within the system, the Miniserver acquires measurements from the point of connection and thermal sensors, processes control logic, and issues control signals to connected devices. These include hot-water actuation via a solid-state relay, supervisory interaction with HVAC systems, and EV enable or scheduling. It also manages communication with external data sources, including inverter telemetry and tariff inputs. The Miniserver therefore acts as the central coordination layer linking measurement, decision-making, and actuation. It is used strictly as a supervisory automation PV inverter and meter integration.

A Fronius hybrid inverter and Smart Meter are used for PV generation and grid import/export measurement. The Smart Meter communicates via Modbus RTU to the inverter, which exposes the data via Modbus TCP using SunSpec models, allowing the EMS to interface with a single endpoint. (Fronius, 2024).

3.9.2. Hot water sensing and PWM actuation

The domestic hot-water cylinder is a 300-litre storage vessel with a resistive element rated at 3 kW. At the power stage, the element is interfaced through an external relay/SSR for proportional PWM actuation when required.

Proportional control is implemented using a PWM-driven solid-state relay, with the duty cycle varied to adjust the effective heating power between zero and 3 kW. This allows the hot-water load to track surplus PV generation in real time rather than operating in discrete on or off steps.

All mains voltage wiring, element switching, and protective devices were installed and verified by a qualified electrician to comply with applicable New Zealand electrical safety requirements including AS/NZS3000.

PWM parameters are selected to avoid excessive switching while still providing adequate modulation resolution for energy management. The EMS therefore treats the SSR and element as an actuator with a continuous input and an effective average electrical-power output over the chosen PWM period.

Hot water control requires a state variable representing stored thermal energy. In practice, stored thermal energy is proxied by tank temperature or a temperature stratification profile. The Case Study measures tank temperature using an installed temperature probe and transmitter that provides a 0 to 10 V signal to the controller’s analogue input.

The analogue temperature measurement serves two roles: constraint enforcement, by keeping the tank above a minimum service threshold and below a maximum bound; and control-state estimation, by allowing the EMS to decide whether hot-water heating can be deferred during peak periods or increased during PV-surplus and low-price windows.

The installed probe is a Pt100 Class A three-wire temperature sensor with a 316 stainless-steel sheath. RTD signal is conditioned using a PR Electronics 5114 programmable transmitter, which accepts RTD inputs, provides three-port galvanic isolation, and supports a configurable voltage output including 0-10 V for controller integration (PR Electronics, n.d.). This Pt100 transmitter analogue input converts hot water thermal state into a stable variable that can be used for both constraint enforcement and supervisory scheduling.

Actuation must also accommodate the electrical duty imposed by the 3-kW element. At 240 V, the corresponding current is approximately 12.5 A, hence the SS Relay was sized to 40A to minimise the likelihood of overheating. Loxone's installation guidance recommends coupling relays for loads above 5 A on Miniserver digital outputs, which supports the use of the controller as supervisory logic only and the delegation of mains switching to an external relay/SSR power stage (Loxone, 2026).

3.9.3. Software structure

At the software level, the Loxone Miniserver acts as an edge controller. It acquires inverter and meter values over Modbus TCP, ingests analogue hot-water temperature, logs states and alarms, and exposes dashboards and manual overrides. In this arrangement, the Fronius inverter operates as the principal telemetry gateway for PV and point-of-connection data.

Physical I/O is reserved for functions that need deterministic local action or are not conveniently exposed through protocol integration. In the present installation this includes the HWC command path and selected supervisory enable signals. Several supervisory modes are implemented: PV self-consumption, peak shaving, price-responsive scheduling, comfort priority override, and minimum-service hot-water recovery. An arbitration layer selects among these modes using calendar rules, user settings, measured temperatures, and charger availability.

In the configurator (Config) the control logic is implemented as two configured control paths. A digital control path uses logic blocks (Greater, Schedule, Less, Analogue Multiplexer, AND/OR, and a hysteretic temperature-control block) to drive relay output Q1. A second path provides analogue immersion heater control through a Proportional Integral (PI) controller, with threshold based overheat protection and fixed duration manual boost (Loxone, 2026).

3.9.4. Active control branches and timing parameters

The deployed hot-water control is implemented as three configured control paths. The first is a relay-based path, which uses a surplus comparator, switched temperature setpoint selection, and hysteretic two-position control to enable heating during PV-surplus or scheduled service periods. The second is an analogue diversion path based on the Loxone Energy Manager, which updates at approximately 60 s intervals and maps measured grid surplus to an immersion-heater command. The third is a PI-based analogue path with approximately 1 s sampling, intended for finer surplus tracking when a continuously variable immersion interface is available.

In practice, the system operates with two actuator paths under the same supervisory objective: a threshold-based diversion using relay control, and a proportional diversion using the analogue path. The EMS records PV generation, grid exchange, temperatures, control states, alarms, and selected override events, supporting troubleshooting and subsequent measurement and verification. Alarm conditions include stale telemetry, loss of communications, hot-water service risk, comfort excursions, abnormal import peaks, and device faults.

Where external inputs are unavailable, the controller falls back to simpler operating modes. If price data are not available, control defaults to PV self-consumption and scheduling logic. If inverter telemetry is lost, surplus-based control is suspended and conservative, service-preserving operation is applied. This reflects the need for robust behaviour under partial failure conditions in mixed protocol systems.

4. Results

Two data sources are analysed and discussed in this section. The first is the retailer customer portal export of daily net site usage and daily net billed amount from 1 August 2025 to 28 February 2026 and a comparison is made between pre installation months (August, September, October) and Post Installation Months of December, January and February). In these datasets, positive daily usage denotes net import from the grid and negative daily usage denotes net export after behind the meter generation has first served onsite demand. The daily billed amount represents the net account outcome for each day, calculated from imported energy charges and fixed daily charges, offset by export credits.

The second data source comprises inverter system portal production traces, which show PV generation, grid export, and site consumption at sub-hourly resolution. In these traces, total site consumption is shown as a blue line, direct on-site use of PV is shown in yellow, and power exported to the grid is shown in grey.

During daylight hours, PV generation increases and creates a surplus where generation exceeds base demand. This surplus is typically exported to the grid unless additional loads are activated. Controlled loads, such as the hot-water cylinder, appear as repeated spikes in the consumption trace, typically in the range of 3–4 kW. These spikes coincide with reductions in export, indicating that surplus PV is being diverted to on-site use.

November 2025 data were not included in the analyses as the system was offline. In addition, the rows for 19-28 February 2026 were all zero as the system was temporarily inactive due to a fault. Consequently, the post commissioning operational window used for statistical summaries is 1 January to 18 February 2026. Two comparison windows are used to distinguish commissioning-related change from broader seasonal variation. August to October 2025 provides the pre-commissioning baseline. A second, tighter comparison is made within December, between 1–10 December and 11–31 December 2025, to capture the abrupt step change in the retailer data when sustained net export begins. At the whole-site level, this discontinuity marks a commissioning boundary, but in the absence of device-level submetering it cannot be attributed to the hot-water controller alone.

It is noted that positive net grid energy denotes daily net import from the grid; negative values denote daily net export. Positive daily account balance denotes a customer cost;

negative values denote a net daily credit. The February operational window excludes ten days (19–28 February 2026) when the system was offline.
Table 4 and Figure 4 show that the premises operated as a consistent net importer throughout the August to October 2025 baseline, with mean daily net grid energy of +10.91 kWh/day and mean daily net account cost of NZD 5.31/day. From 11 December 2025 onward, daily values become consistently negative, with export recorded on all remaining days in December.

Table 4. Summary of measured whole facility outcomes from retailer daily net-usage data

Evaluation window	Days	Mean daily net grid energy (kWh/day)	Net grid energy (kWh)	Mean daily net account balance (NZD/day)	Net account balance (NZD)	Export days
Aug-Oct 2025 baseline	92	10.91	1003.96	5.31	488.14	0
1-10 Dec 2025 pre-comm.	10	12.74	127.42	5.98	59.84	0
11-31 Dec 2025 post-comm.	21	-38.84	-815.58	-3.36	-70.57	21
1 Jan-18 Feb 2026 operational	49	-34.99	-1714.75	-2.37	-116.01	48

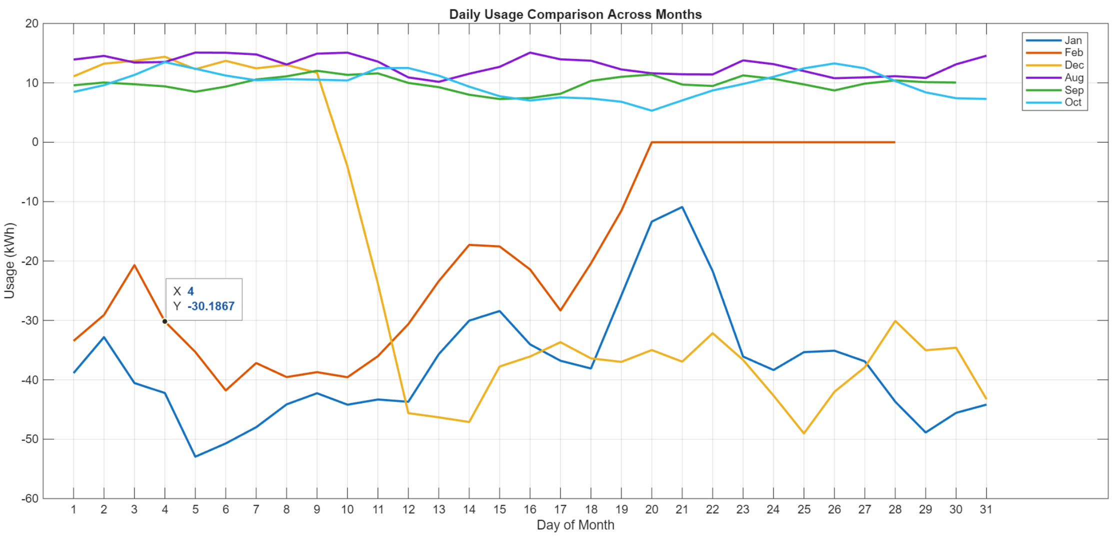

Figure 4. Retailer recorded daily net grid energy from 1 August 2025 to 28 February 2026

This operating state continues into January and mid-February, where values remain predominantly below zero across the month. Over the operational window from 1 January to 18 February 2026, mean daily net grid exchange is −34.99 kWh/day and mean daily net account balance is −NZD 2.37/day, with export recorded on 48 of 49 valid days.

Figure 5 shows daily net grid energy with periods of no control (August–October), transition (1–10 December), and active supervisory control (from 11 December onward) highlighted. From August through 10 December, the site operates in net-import mode, with daily values consistently positive and relatively stable. During 1–10 December 2025, mean daily net grid energy is +12.74 kWh/day and mean daily net account balance is +NZD 5.98/day.

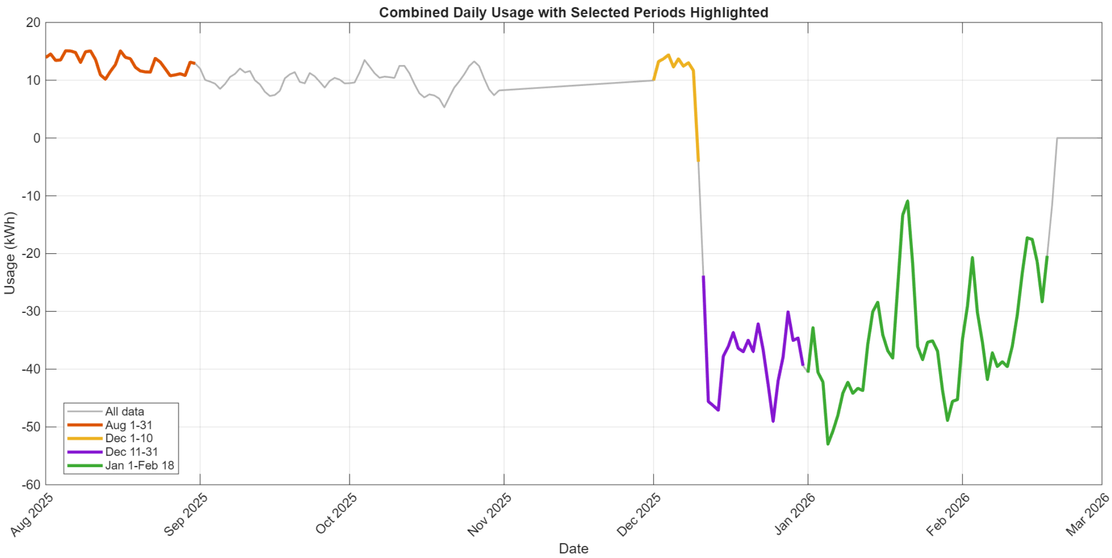

Figure 5. Mean daily net grid energy and mean daily net account balance across the main evaluation windows

From 11 December onward, daily values shift abruptly into negative territory and remain negative for the rest of the month. For 11–31 December 2025, mean daily net grid energy is −38.84 kWh/day and mean daily net account balance is −NZD 3.36/day. This corresponds to a change of 51.58 kWh/day in net grid exchange and NZD 9.34/day in daily account outcome. All valid days after 10 December are net-export days.

4.1. Daily production profiles and implemented relay logic

The hot-water control system operates by aligning flexible demand with periods of PV generation. On days where control is active, the hot-water cylinder is driven during the solar window to utilise available surplus, while operation is reduced outside this period. The resulting operating behaviour is observed using inverter system portal production traces over two periods, 11–23 December 2025 and 28 February–13 March 2026. Hot-water diversion is identified where the direct-consumption trace increases by approximately 2.5–3.5 kW above the daytime baseload, accompanied by a corresponding reduction in export. Days with repeated events of this form are controlled scenario, while days without such events, characterised by smooth export profiles and demand close to baseload, are recorded as little no control days. The percentages derived from these traces are visual estimates based on comparison between direct consumption and total production.

Figure 6 shows representative production traces. Grey denotes export, yellow direct PV use, and blue total site demand. Clear diversion days show repeated daytime increases in direct consumption of approximately 2.5–3.5 kW above baseload, with corresponding reductions in export. Days with little or no diversion show smoother export profiles with only isolated daytime demand spikes.

Panels (a) 21 December 2025 and (b) 4 March 2026 show repeated daytime direct-consumption blocks that are consistent with surplus-driven hot-water heating. In contrast, panels (c) 3 March 2026 and (d) 10 March 2026 are export-dominated days where little or no diversion signature is visible.

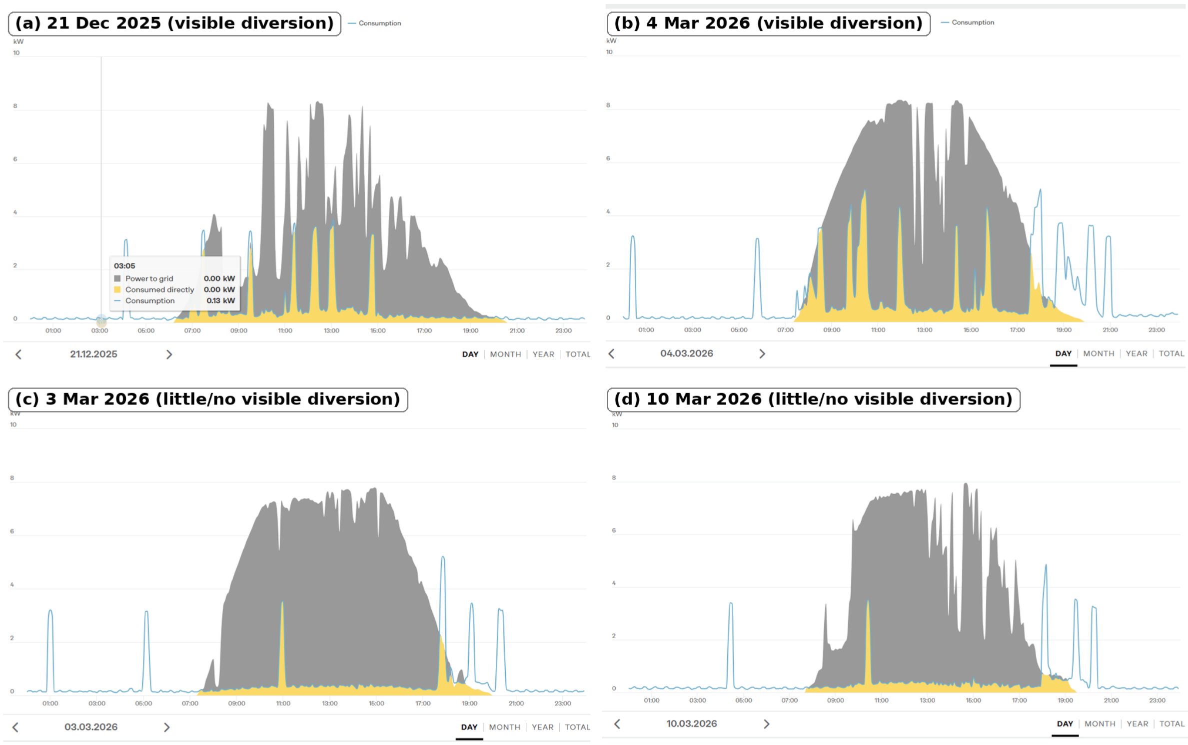

Figure 6. Selected Inverter Portal production-view contrasting days with visible surplus-driven hot-water diversion and days with little/no visible diversion

Table 5 summarises the full 27-day archive. Diversion signatures were characterised by repeated daytime HWC-sized load additions aligned with solar production; little/no-diversion days retained broad export domes and near-baseload direct consumption; mixed days showed one or two qualifying events but not a consistently strong daytime diversion pattern.

Table 5. Qualitative classification of the 27-day by visible hot-water diversion signature

Class	Dates	Main visual signature and interpretation
Clear visible surplus-diversion signature (n = 13)	13, 14, 16, 17, 20, 21 Dec 2025; 28 Feb 2026; 1, 4, 6, 8, 11, 13 Mar 2026	Repeated HWC-sized daytime direct-consumption additions with visible notches in export; consistent with surplus-driven hot-water heating.
Mixed / partial diversion signature (n = 6)	11, 12, 18, 19 Dec 2025; 7, 12 Mar 2026	One or two qualifying daytime events or a weaker diversion pattern that is insufficient for clean semi-quantitative comparison.
Little or no visible diversion signature (n = 8)	15, 22, 23 Dec 2025; 2, 3, 5, 9, 10 Mar 2026	Broad export dome and near-baseload direct consumption through most solar hours; little evidence of sustained daytime HWC diversion.

Figure 7 consolidates the implemented block-level hot-water logic. Panel (a) shows the relay branch associated with the discrete 3 kW signatures in the Fronius day plots. A Greater block generates the surplus-permission signal by setting G = 1 when V1 exceeds V2, an Analogue Multiplexer selects the active temperature target, the two-position controller applies a hysteresis band, and Q1 is energised only when the selected temperature condition and the morning-service or PV-permission logic are jointly satisfied. Panel (b) reproduces the hysteretic timing behaviour of the two-position controller, which explains the stable on/off operation visible on relay-dominant days. Panel (c) shows the alternative analogue diverter branch, in which either the Energy Manager or the PI Controller drives the immersion-heater output subject to overheat protection and manual boost.

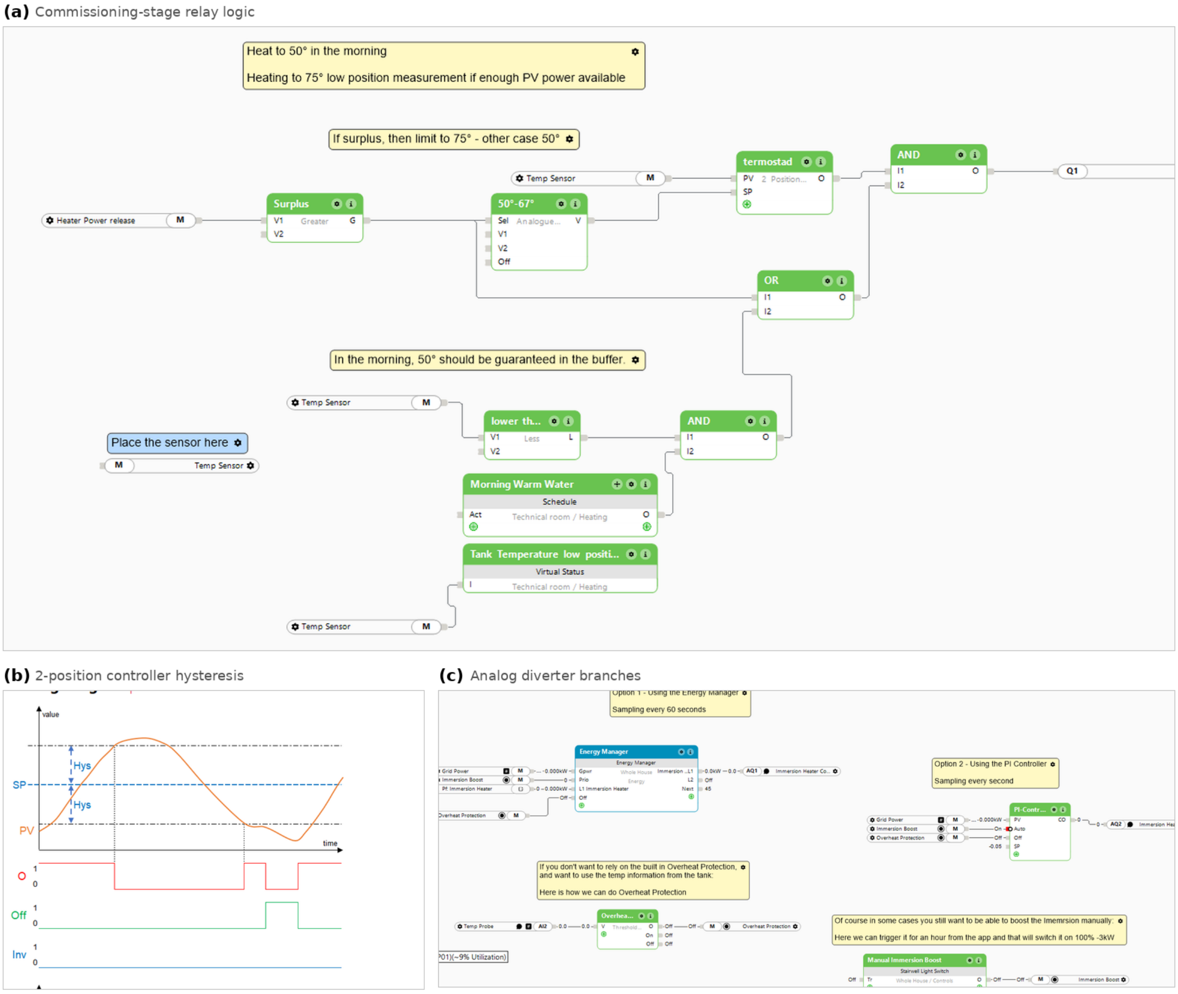

Figure 7. Implemented domestic hot-water control branches

Comparative indicators were derived from a 15-day subset of clearly interpretable screenshot days. Mixed days were excluded to limit ambiguity. Likely HWC events were coded as direct-consumption excursions of roughly 2.5-3.5 kW above the daytime baseload; self-consumption and export shares were then approximated from the relative areas of the yellow and grey traces.

Table 6 and Figure 8 show materially different operating patterns between the two classes. High-diversion days were associated with substantially higher approximate PV self-consumption than low-diversion days (31.3% versus 12.7%), together with a lower export share (68.7% versus 87.3%) and a much higher count of daytime HWC events (4.7 versus 0.8 per day). In comparative terms, the analysis indicates an approximate increase of 18.6 percentage points in self-consumption, a reduction of 18.6 percentage points in export share, and nearly a fivefold increase in daytime HWC event frequency.

Table 6. Comparative indicators

Metric	**Little/no visible diversion**	**Visible diversion**	**Change associated with visible diversion**
Approx. self-consumption (%)	12.7	31.3	+18.6 percentage points (+146% relative)
Approx. export share (%)	87.3	68.7	-18.6 percentage points (-21% relative)
Daytime HWC events/day	0.8	4.7	+3.9 events/day (+487% relative)

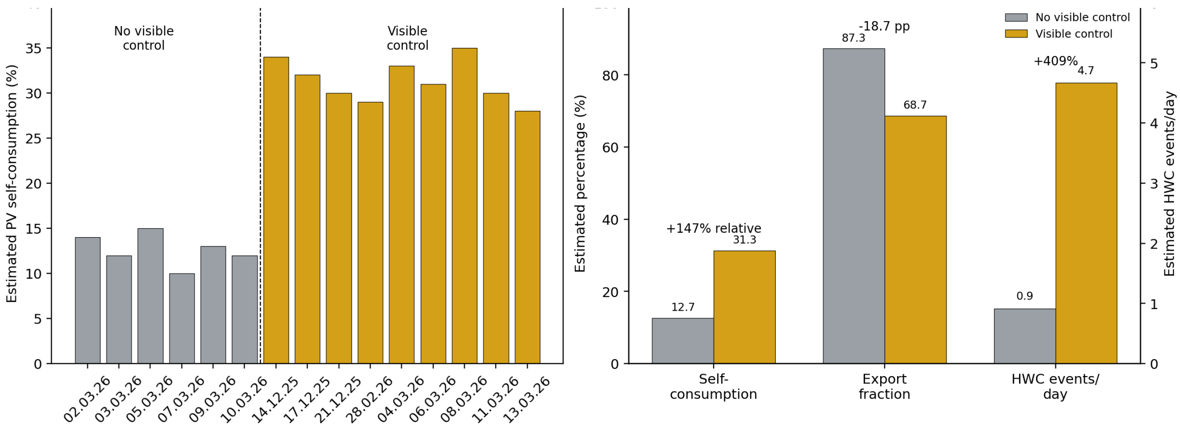

Figure 8. Approximate comparative indicators from a 15-day subset of visually coded day plots

A comparison was also made between relay based on/off switching and PWM based control. Figure 9 shows 22 December (no control), 21 December (relay on/off), and 17 December (PWM-type operation).

The operating patterns shown in Figure 9a are reflected in the relative changes in Figure 9b. The no-control case is characterised by smooth export-dominated profiles with little interaction between load and PV generation. Under relay-based on/off control, hot-water demand appears as discrete 3 kW spikes during the solar window, producing intermittent reductions in export. Under PWM control, these spikes become more frequent and distributed, with demand more closely tracking available PV. Both control strategies increase direct PV use and hot-water supply from PV, while reducing grid import and hot-water energy drawn from the grid. The larger shifts under strict control reflect the more continuous utilisation of surplus PV observed in the PWM traces compared to the discrete behaviour of relay-based control.

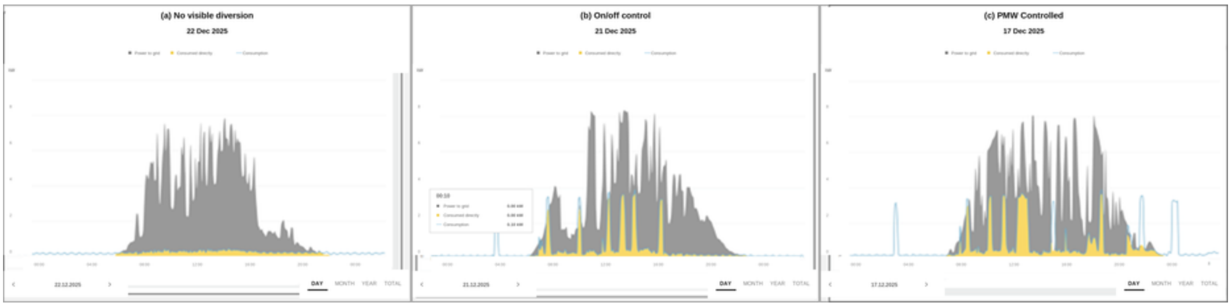

Figure 9a. Representative visual signatures drawn from the December screenshot archive.

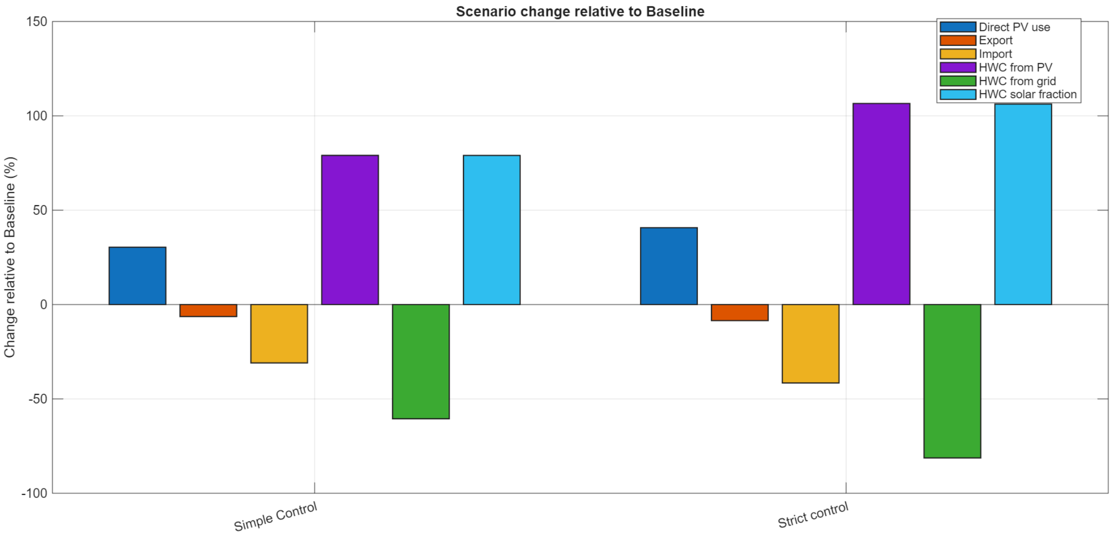

Figure 9b. Scenario change relative to baseline

4.2. Single-day hot-water scheduling model

To complement the portal visual analysis, a supplementary single day reconstruction and allocation model was developed for 13 March 2026 from a digitised inverter dashboard trace. The reconstructed profile was balanced minute by minute so that direct PV use, export, and import satisfied the site energy identities. The digitised daily PV total differed from the dashboard total by 0.25%, which is sufficiently close for explanatory analysis. Over the reconstructed day, total PV production was 34.57 kWh and total site consumption was 11.85 kWh, of which 5.99 kWh was supplied directly by PV, 5.85 kWh was imported from the grid, and 28.57 kWh was exported.

The hot water cylinder accounted for an estimated 5.28 kWh, or 44.6% of total site consumption, confirming that it was the dominant flexible load on the selected day. Several reheating events occurred outside effective PV-surplus periods, particularly in the early morning and evening, making the day analytically useful because it contains both substantial PV surplus and clear opportunities for load shifting. Under the balanced baseline, 2.29 kWh of cylinder energy was supplied by PV and 2.99 kWh by the grid, giving a hot-water solar fraction of 43.4%.

Two counterfactual scheduling scenarios were then applied to the same daily hot water energy requirement. The first was a conservative shift-only case in which clearly non-solar reheating periods were relocated into later PV surplus windows. The second was a stricter case that preserved the morning minimum service top up while preferentially allocating the remaining hot water demand to surplus PV periods up to the higher storage target indicated in the supplied control logic. In both cases, total daily thermal demand remained unchanged; only the timing and source of water heating energy were changed.

Figure 10a shows the scenario comparison for the reconstructed day. The observed case is used as the reference, representing the actual timing and allocation of energy. Under both alternative scenarios, total hot-water demand remains unchanged, but its timing is shifted into periods of PV availability. This increases direct PV use from 5.99 kWh/day to 7.81 kWh/day (simple control) and 8.43 kWh/day (strict control), while export and grid import decrease accordingly. The shift is most evident in hot-water supply, where energy from PV increases (2.29 to 4.10 and 4.73 kWh/day) and energy from the grid decreases (2.99 to 1.18 and 0.56 kWh/day). The strict control case produces the largest change, reflecting a more complete alignment of hot-water demand with available PV generation.

It is noted that the modelled cases preserve the same total daily hot-water energy requirement as the observed case and change only its timing and energy source. The strict control case retains the morning minimum service top up while shifting the remaining requirement into PV-surplus windows.

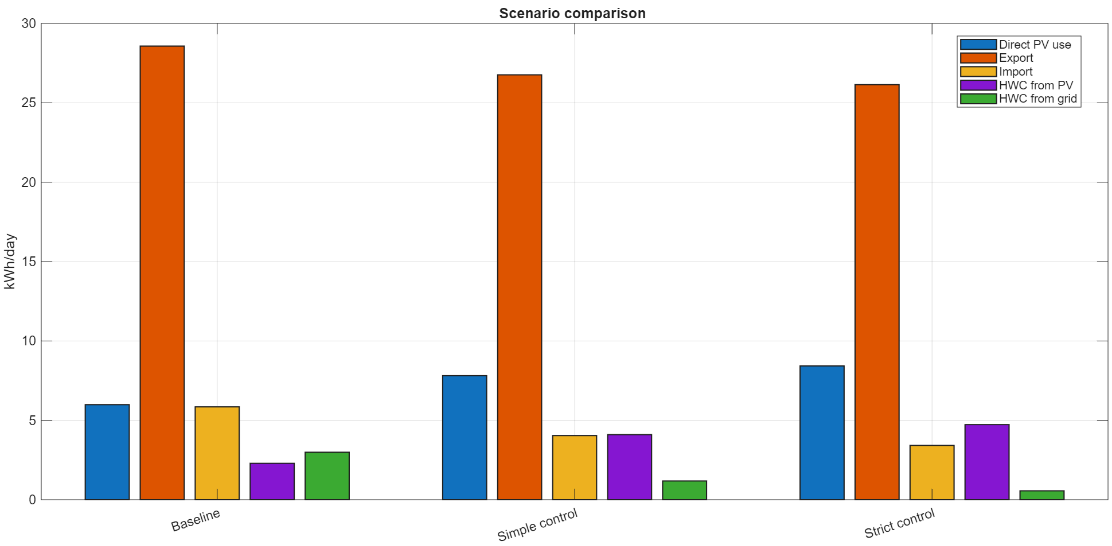

Figure 10a. Scenario comparison

Table 7 and Figure 10b report the resulting comparison. In the conservative case, grid import falls from 5.85 to 4.04 kWh/day, and direct PV use rises from 5.99 to 7.81 kWh/day, while the hot-water solar fraction increases from 43.4% to 77.7%. In the stricter control case, grid import falls further to 3.42 kWh/day, a reduction of 41.6% relative to the observed baseline. Direct PV use rises to 8.43 kWh/day and export falls to 26.14 kWh/day as energy that would otherwise have been exported is stored as hot water. Within the cylinder load itself, grid-supplied energy falls from 2.99 to 0.56 kWh/day and the hot-water solar fraction rises to 89.5%.

Table 7. Modelled 13 March 2026 outcomes for the observed and. alternative hot-water scheduling scenarios

Scenario	Direct PV use (kWh/day)	Export (kWh/day)	Import (kWh/day)	HWC from PV (kWh/day)	HWC from grid (kWh/day)	HWC solar fraction
Observed Balance/ Referenced Baseline	5.99	28.57	5.85	2.29	2.99	43.4%
Shift only dark events	7.81	26.76	4.04	4.10	1.18	77.7%
Strict control	8.43	26.14	3.42	4.73	0.56	89.5%

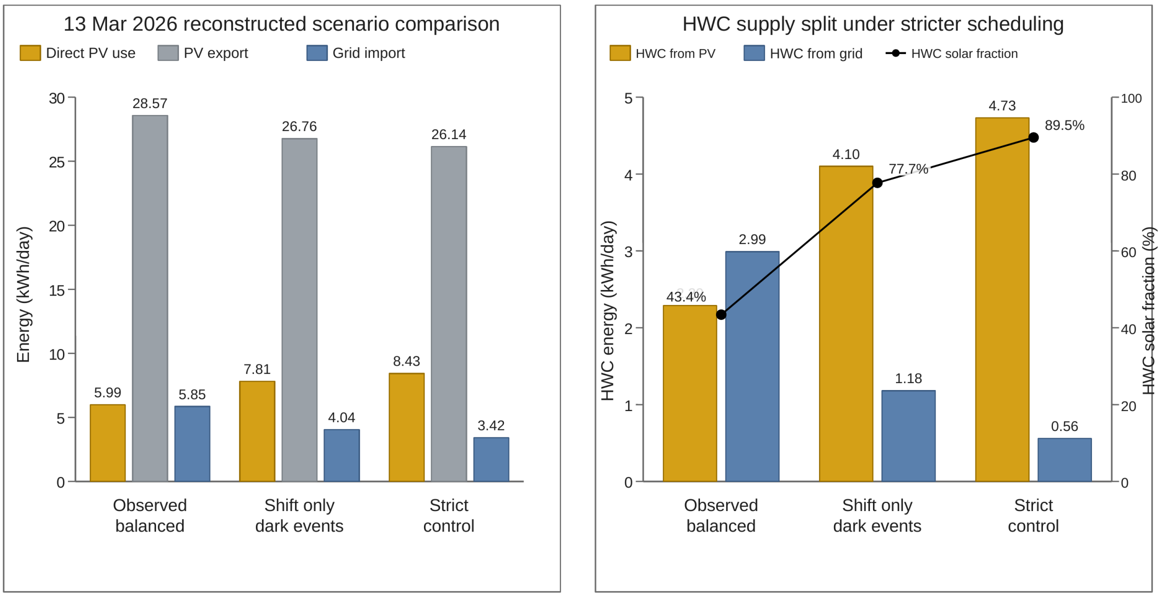

Figure 10b. Comparison of the observed balanced case with two alternative hot-water scheduling cases

PV self-consumption is the ratio of direct PV use to total PV production, and solar self-sufficiency is the ratio of direct PV use to total site consumption. On this basis, PV self-consumption rises from 17.3% in the observed case to 24.4% in the stricter case, while solar self-sufficiency rises from 50.6% to 71.1%. Daily net grid exchange remains -22.72 kWh/day in all three cases because each kilowatt-hour shifted from night-time import to daytime self-consumption reduces import and export by the same amount. The model clarifies how tighter hot-water scheduling changes the balance between grid imports and exports on a high-sola surplus day. In Figure 10 below, the left panel compares the observed trace with the strict scheduling case for the same daily hot-water energy requirement; the right panel summarises the resulting shift in hot-water energy supply from the grid toward PV.

4.3. Established findings and remaining evidence gaps

The evidence supports three main findings. First, retailer data shows a clear shift from routine daily net import and daily cost to sustained net export and daily credit after commissioning. Second, the 27-day screenshot archive shows repeated surplus-driven diversion patterns, and the 15-day comparison subset indicates higher PV self-consumption and lower export on days with visible diversion. Third, the 13 March reconstruction shows that stricter hot-water scheduling can reduce imports and raise site self-sufficiency on a high-surplus day, even when daily net grid exchange remains unchanged. In that case, the benefit appears in the balance between imports and exports rather than in the daily net total.

Interval import/export metering, hot water submetering, and direct temperature and relay logs would strengthen subsystem attribution. Within the present evidence base, whole-site measurement, operating-signature analysis, and allocation modelling provide mutually consistent evidence of the commissioning outcome.

Temperature sensing, schedule logic, and alarms were implemented for both the cylinder and occupied zones, but the present dataset does not include a longitudinal compliance analysis of minimum hot-water service temperature, room-temperature comfort, or override frequency. The demonstrated field outcomes therefore relate primarily to whole-site power-flow behaviour, diversion signatures, and the single-day hot-water allocation model.

5. Discussion

5.1. Practical implications for households, SMEs, and aggregators

For households and SME, the main implication is that meaningful gains in PV use do not necessarily require immediate battery investment. A local supervisory layer can increase self consumption by shifting hot water heating and other flexible loads into solar rich or lower price periods, provided that hot water sufficiency, thermal comfort rules are not violated and manual override remain explicit. This points to a staged pathway in which households first improve control of existing flexible loads and only later consider more capital intensive assets such as batteries.

Small commercial sites often have more regular occupancy schedules, larger HVAC loads, clearer operating windows, and stronger incentives to manage demand charges or time varying prices. The approach set out here can be applied to offices, workshops, retail sites, and light-industrial premises with different asset sizes but similar supervisory requirements. The transferable element is not a single vendor stack but a clear control boundary separating telemetry, constraints, supervisory commands, and protective authority.

For aggregators and portfolio owners, the case study highlights the need for a common data model as much as for physical device connectivity. A portfolio is unlikely to consist of a standardised device stack. Aggregation is more tractable when premises architectures normalise heterogeneous devices into common variables such as point of connection power, thermal state, charger availability, site limits, and override status. On that basis, the case study site is better understood as a template for portfolio level orchestration.

Adoption is not solely a technical question. Occupants and site managers need control systems they can understand, override, and trust. Visible service thresholds, manual boost functions, conservative defaults, and clear alarm behaviour may matter as much for real uptake as marginal gains in optimisation performance. Simple rule-based logic remains relevant alongside more advanced control because interpretable behaviour reduces commissioning risk and improves user acceptability.

5.2. Implications for New Zealand's flexibility transition and policy

This case study speaks directly to New Zealand's wider flexibility transition. National flexibility potential will only be realised when tariff and policy signals are translated into premises level sensing, constraint management, and reliable local control. The Case offers one example of how that translation can be achieved with commercially available components. It also shows the limits of price reform on its own: a time-varying tariff does not automatically produce useful demand response. End users still need controllers that can interpret the signal while maintaining hot water service, comfort, and charging obligations (EECA, 2026; Electricity Authority, 2025).

Market design, technology standards, and data access need to develop together. Flexibility products are more credible when premises controllers can expose auditable state variables and clearly bounded control capability. Retail time varying plans are more useful when customers or service providers can obtain machine readable consumption and export data in a timely form. New Zealand's current work on demand flexibility products, smart EV charging, and dynamic pricing moves in that direction, but the premises layer remains the point at which system objectives meet service constraints and occupant acceptance (; MBIE, 2025; Electricity Authority, 2025).

There is also an equity dimension. More dynamic pricing and more active control can create value, but they can also shift risk onto consumers who lack automation, digital confidence, or the capital to install enabling equipment. A just flexibility transition therefore requires low friction control options, transparent override rights, conservative defaults, and business models that do not depend on exposing households to unmanaged price volatility.

6. Conclusion

This paper documents the design, implementation, and initial field evidence of a distributed energy management and SCADA system for PV and flexible loads at a residential site. The results indicate that building automation-based demand flexibility can improve local solar use through load shifting without battery storage. More broadly, the case study shows how a building automation controller can coordinate flexible loads and make the consequences of different control modes visible through implementation evidence, whole site outcomes, and analysis of inverter traces.

6.1. Recommendations

Three recommendations follow from the case study. First, premises-level implementations should prioritise explicit service constraints over purely economic schedules. Minimum hot-water service, comfort bounds, charger deadlines, manual boost, and safe fallback are not peripheral features; they are the conditions under which flexibility remains acceptable and scalable.

Second, implementations should preserve a clean separation between supervisory control and protective authority. Native inverter, charger, thermostat, and thermal safety functions should continue to act as the primary protection layer, while the EMS provides higher level optimisation and coordination.

Third, market and policy development should support interoperable, auditable flexibility. That points toward better machine-readable customer data, clearer interfaces between retailer tariffs and premises controllers, support for smart charging interoperability, and standardised descriptions of flexible load capability. From a research perspective, the next step is a longer duration, interval metered multi asset trial that combines site-boundary outcomes with direct logs for hot water temperature, relay and analogue outputs, HVAC state, and EV Charging.

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