



VEHICLE-TO-HOME (V2H) SYSTEMS: A Practical and Technical Guide

HANDBOOK

**GRID INTEGRATION LAB
INDIAN INSTITUTE OF TECHNOLOGY BOMBAY**
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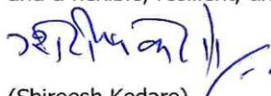


Foreword

The rapid growth of electric mobility is bringing the transportation and electricity sectors closer together than ever before. Global electric-car sales have increased multifold, creating a growing requirement for flexibility, energy storage, demand-side management, and other balancing resources within electricity systems. Through coordinated smart charging, the energy stored in vehicle batteries can potentially support homes, commercial facilities, charging depots, distribution networks, and the wider power system in handling high share of renewable. Technologies such as Vehicle-to-Grid (V2G), Vehicle-to-Home (V2H), and intelligent charging therefore offer an important opportunity to make electric mobility an active participant in the transition towards a more flexible, resilient, and sustainable energy system. The opportunity is particularly significant for India. As of August 2026, more than 10 million electric vehicles (EVs) were registered in the country, alongside the continuing expansion of renewable generation and charging infrastructure. However, practical issues about charging time, charging period, willingness & convenience of stakeholders need to be taken into account while developing & implementing the related technology.

Indian Institute of Technology Bombay is committed to contributing to this transition through technically rigorous, implementation-oriented research and close engagement with utilities, government agencies, industry, technology providers, and other stakeholders. The reports developed under **Vehicle to Grid (V2G) Study** undertaken by **Grid Integration Lab** at the Department of Energy Science and Engineering, IIT Bombay and funded by Federal Ministry for Economic Cooperation and Development (Germany) through Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), address different complementary dimensions of this emerging ecosystem and associated energy transition. Together, they aim to provide a comprehensive technical and strategic knowledge base for the safe, interoperable, reliable, economically sustainable, and scalable integration of electric vehicles with India's power system.

I would like to congratulate the **Grid Integration Lab**, authors, researchers, reviewers, participating stakeholders, and supporting organisations whose contributions have made this work possible. I hope that the outcomes of the project will contribute meaningfully to the development of an enabling ecosystem for bidirectional electric mobility in India and support the country's broader transition towards clean transportation and a flexible, resilient, and low-carbon energy future.


(Shireesh Kedare)



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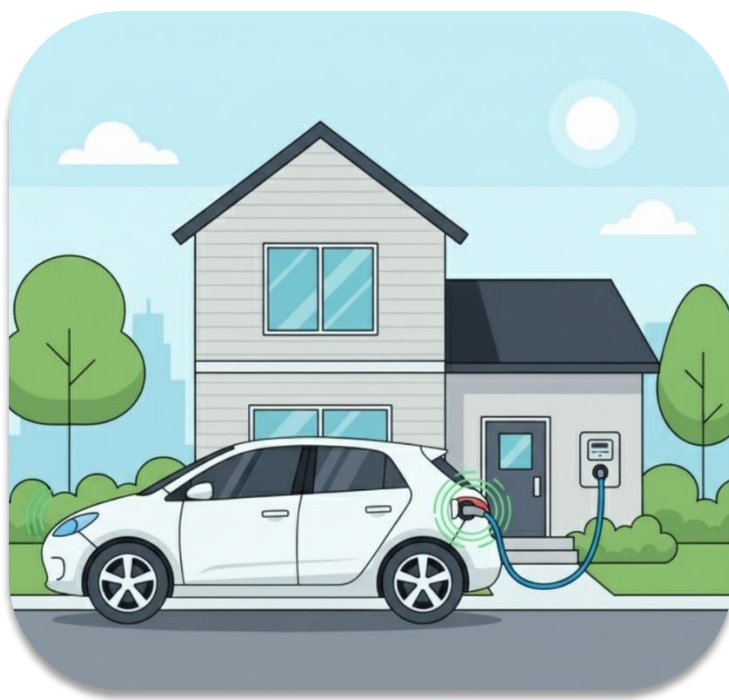


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Abbreviations

- **BEV:** Battery Electric Vehicle
- **CA:** Certificate Authority
- **DER:** Distributed Energy Resource
- **EV:** Electric Vehicle
- **EVSE:** Electric Vehicle Supply Equipment
- **G2V:** Grid-to-Vehicle
- **HEMS:** Home Energy Management System
- **IDS:** Intrusion Detection System
- **IEC:** International Electrotechnical Commission
- **IEEE:** Institute of Electrical and Electronics Engineers
- **ISO:** International Organization for Standardization
- **LMS:** Load Management System
- **MCB:** Miniature Circuit Breaker
- **NIST:** National Institute of Standards and Technology
- **NPV:** Net Present Value
- **NTP:** Network Time Protocol
- **O&M:** Operations and Maintenance
- **OCPP:** Open Charge Point Protocol
- **OEM:** Original Equipment Manufacturer
- **PKI:** Public Key Infrastructure
- **PV:** Photovoltaic
- **RCD:** Residual Current Device
- **RE:** Renewable Energy
- **SOC:** State of Charge
- **TLS:** Transport Layer Security
- **TOU:** Time-of-Use
- **V2G:** Vehicle-to-Grid
- **V2H:** Vehicle-to-Home
- **V2L:** Vehicle-to-Load
- **V2X:** Vehicle-to-Everything



Executive Summary

This report provides a comprehensive technical and practical overview of Vehicle-to-Home (V2H) systems, with emphasis on their architecture, operation, control, grid interaction, and potential role in future residential energy systems. It examines the major V2H system configurations and functional components, including bidirectional charging infrastructure, home energy management systems, metering, protection, communication interfaces, and renewable-energy integration. The report further discusses power-flow control and optimization strategies, power-quality and stability considerations, instrumentation and diagnostic requirements, and representative commercial products and field demonstrations. Real-world deployment experiences, including residential backup applications and utility interconnection procedures, are considered to illustrate the practical requirements for safe and reliable V2H implementation. In addition, the report evaluates the techno-economic and environmental implications of V2H operation, including electricity-cost reduction, renewable-energy utilization, resilience, investment viability, and emission reduction potential. Interconnection codes, communication protocols, cybersecurity requirements, and relevant technical standards are also reviewed to identify the regulatory and interoperability considerations associated with widespread deployment. Collectively, the report is intended to serve as a structured technical reference for understanding the design, operation, performance, and implementation requirements of V2H systems and their emerging role in smart, flexible, and resilient residential energy networks.

1. Introduction

Vehicle-to-Home (V2H) is a bidirectional energy transfer mechanism in which an electric vehicle (EV), equipped with appropriate hardware and control protocols, supplies stored battery energy to meet residential electricity demand, enabling the EV to function as a portable energy storage unit for emergency backup, behind-the-meter optimization, and other home power needs.

A simple architecture of this is shown in Figure 1, illustrating how an EV can interact with solar, home loads, and the grid via a bidirectional charger to enable both V2H and V2G operations. With different possible control mechanisms as shown in Figure 2, vehicle discharges its energy either in controlled way or uncontrolled way. This flexibility makes the EV an integral component of a dynamic and decentralized

energy ecosystem. The scope of V2H spans beyond emergency backup to continuous applications like energy arbitrage (buying power when cheap, using it when expensive), renewable integration, and demand response.

It enhances grid resilience by enabling EVs to act as mobile backup generators during power outages or disasters, powering essential home loads. EVs with large batteries (~60–100 kWh) can support a household's essential load for multiple days. Unlike stationary batteries, V2H-capable EVs offer energy mobility, allowing users to recharge elsewhere and return with power during extended outages. This mobility also supports broader community resilience, enabling energy sharing with relief centres or neighbours, aligning with the smart grid's decentralized reliability goals.

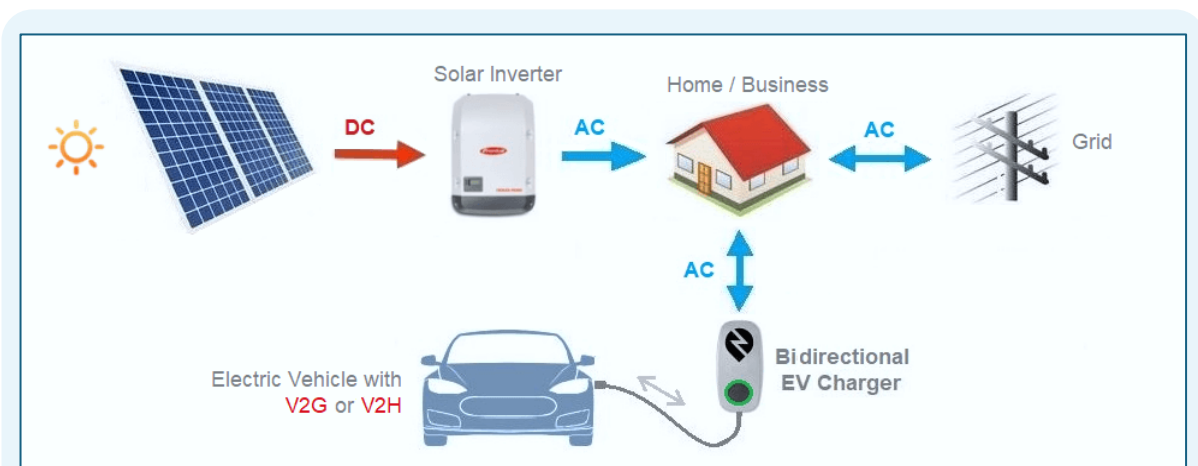


Figure 1: Simplified concept of a bidirectional EV charging system enabling V2H operation. The EV's battery can be charged from the grid or solar (G2V mode) and can discharge through a bidirectional inverter/charger to supply the home (V2H) or even export to the grid (V2G).

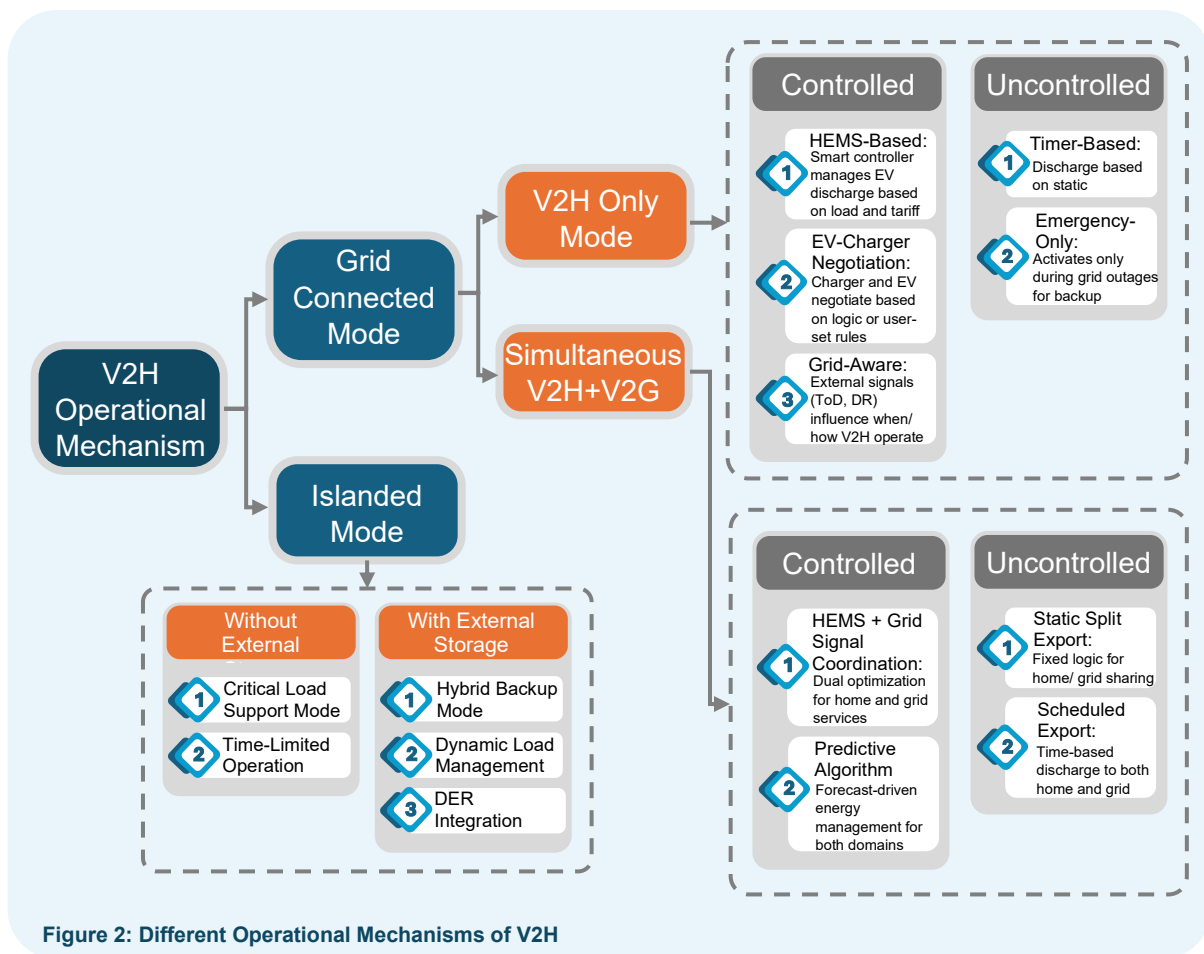


Figure 2: Different Operational Mechanisms of V2H

1.1 Role in Smart Grid

Smart grids are designed to establish digital, decentralized, and data-driven energy networks, as illustrated in Figure 3. V2H systems inherently complement this vision through their dynamic, responsive, and distributed capabilities, enabling intelligent energy flow between the home, vehicle, and grid. Representative use cases demonstrating these capabilities are depicted in Figure 4.

By enabling bidirectional energy flow between electric vehicles and residential loads, V2H supports real-time demand-side flexibility, allowing load shifting from peak to off-peak hours. This not only aids in flattening demand curves but also mitigates

transformer stress in distribution systems. V2H further enhances the grid's ability to integrate variable renewable energy by absorbing excess solar generation during midday and enabling deferred consumption, thus reducing curtailment and increasing local self-consumption.

Additionally, V2H empowers consumers to actively participate in dynamic tariff markets, optimizing electricity costs through time-of-use strategies. Importantly, V2H contributes to grid resilience by offering backup power during outages and enabling energy continuity in emergencies. Its mobile and scalable nature allows deployment beyond individual homes to critical infrastructure, reinforcing the decentralized reliability objectives of the smart grid vision.

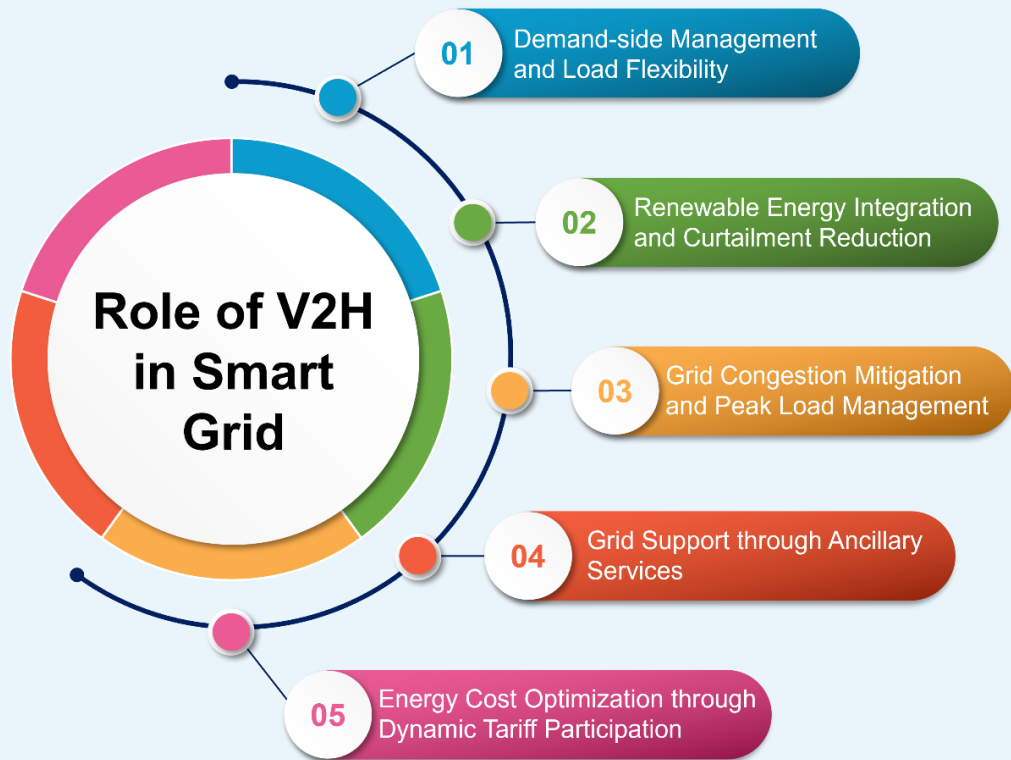


Figure 3: Role of V2H in Smart Grid

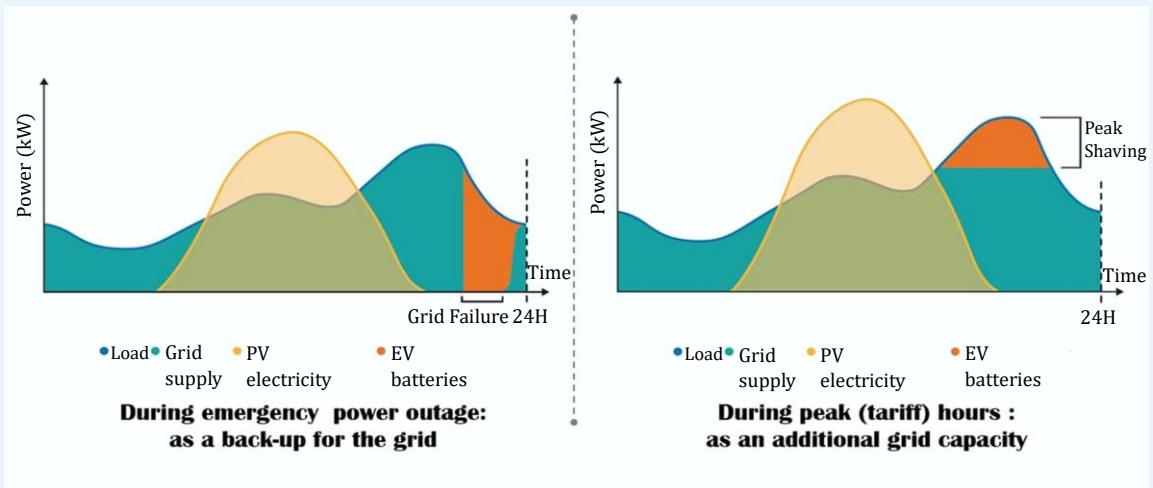


Figure 4: Use Cases of V2H

2. System Architecture and Functional Components of V2H Systems

There are many possible architectures for a V2H system. The most commonly used are: Peak Load Management Architecture, Local Renewable Energy Maximization Architecture, and Islanded Operation Architecture, as illustrated in Table 1. Each architecture comprises key components such as a bidirectional charger, distribution board, Local Management System (LMS),

and standard communication protocols to facilitate controlled energy flow between the electric vehicle (EV) and the home. The system is further supported by smart meters, protection devices, and optional energy storage, enabling effective load management, cost optimization, and enhanced resilience within smart grid environments.

Table 1: Possible Architectures of V2H Operation

Possible Architectures of V2H Operation		
	Components Involved	Description
Peak Load Management Architecture (Figure 5)	Distribution Board, EVSE, LMS, Smart Meter, Sub Meter, EV	- EVSE enables bidirectional energy flow between EV and home. - LMS (Load Management System) coordinates charging/ discharging based on peak hours. - Smart meter records total household energy usage for grid interaction and billing. - Sub-meter separately tracks EV-specific energy usage for system optimization. - During peak tariff periods, the EV discharges energy to the home to minimize grid import. - Communication links between EV, LMS, and metering systems ensure real-time control and data exchange. - System leverages time-of-use pricing to reduce electricity cost.
Local Renewable Energy Maximization Architecture (Figure 6)	Distribution Board, EVSE, LMS, Smart Meter, Sub Meter, EV, On-site Renewable Source (e.g., PV), Optional ESS	- Integrates local renewable generation (e.g., solar PV) to supply household and EV demand. - LMS optimizes charging/discharging to prioritize renewable self-consumption. - Smart meter monitors total energy import/export, enabling real-time adjustments and utility communication.

Possible Architectures of V2H Operation

	Components Involved	Description
Local Renewable Energy Maximization Architecture (Figure 6)		- Sub-meter isolates EV consumption for performance tracking. - Optional Energy Storage System (ESS) stores excess RE for later use. - Surplus renewable energy not used locally can be exported to the grid through RE Export path. - RE usage is maximized, curtailment is reduced, and grid dependence is minimized.
Islanded Operation Architecture (Figure 7)	Distribution Board, EVSE, LMS, Smart Meter (local use), Sub Meter, EV, Local Loads, On-site Renewable Source, Optional ESS	- Operates fully disconnected mode from the grid (islanded mode); grid import is disabled. - On-site renewable energy (e.g., solar PV) is the primary power source. - EV and optional ESS serve as dispatchable energy sources to meet critical local loads. - LMS coordinates energy supply from EV, storage, and renewables based on real-time demand and SoC. - Smart meter provides local energy logging and system awareness but not grid billing. - Sub-meter tracks EV energy uses separately to support energy accounting and control logic. - EVSE enables bidirectional energy flow between EV and household/local loads. - Ensures system resiliency and continuity of supply during prolonged outages or in off-grid settings.

The three architectures depicted illustrate practical implementations of V2H systems under varying operational modes¹.

Figure 5 (Peak Load Management) showcases a grid-connected setup where the Load Management System (LMS) coordinates with the EV and smart meters to shift energy use and mitigate peak demand.

Figure 6 (Local Renewable Energy Maximization) highlights the integration of on-site renewable energy and optional storage to prioritize local generation for EV

charging and household loads, with the capability to export excess energy.

Figure 7 (Islanded Operation) presents a grid-independent configuration where local generation and storage fully support the home and EV, enabling resilient energy supply during outages.

These architectures, as detailed in our published book chapter 1, demonstrate how coordinated control and bidirectional energy flow enhance flexibility, sustainability, and grid support.

¹ Mitra, Indradip, Zakir Rather, Angshu Nath, and Sahana Lokesh. 2023. "Electric Vehicles as Smart Appliances for Residential Energy Management." In *Energy Smart Appliances: Applications, Methodologies, and Challenges*, 263–300. IEEE.

2.1 Schematic while using vehicle as a storage

Figure 8 shows the wiring layout for a V2H-enabled home, integrating grid supply, EVSE, and energy storage. It separates

high-priority and low-priority loads, with the Load Management System (LSM) coordinating control signals to the EVSE and energy storage controller. A backup isolator ensures safety during grid disconnection, while protective devices like RCDs and MCBs safeguard the system.

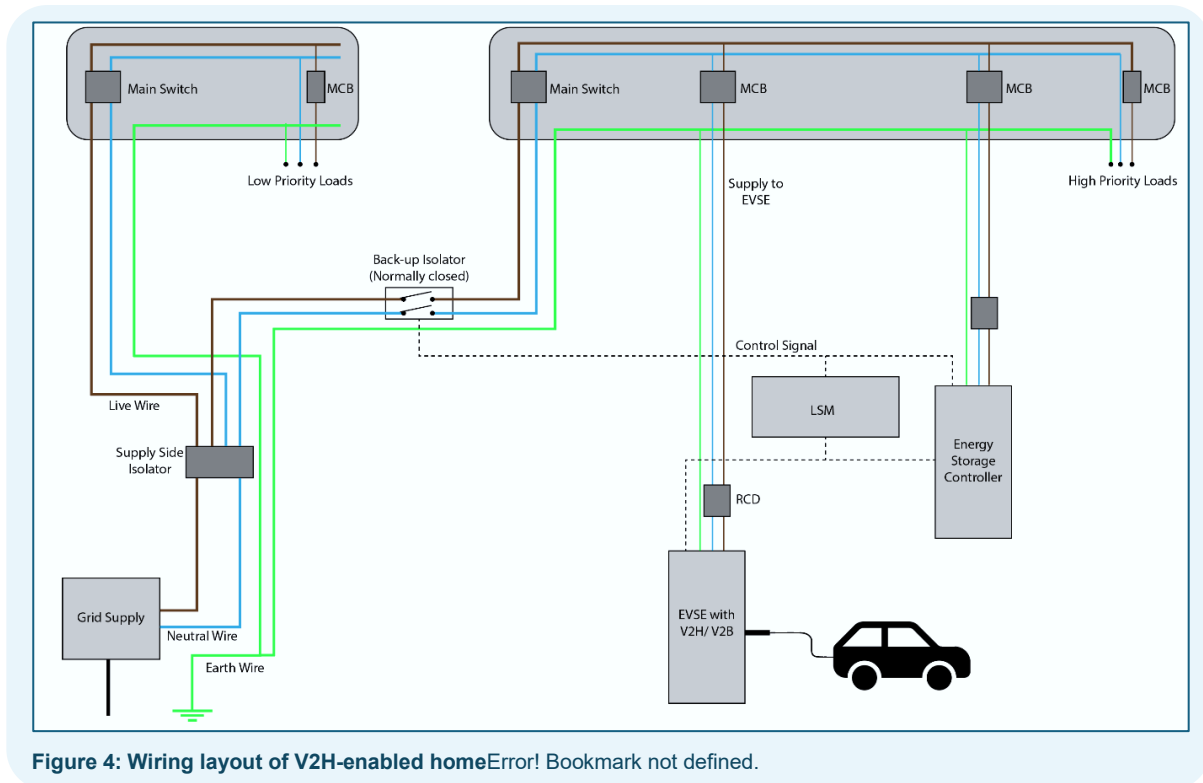


Figure 4: Wiring layout of V2H-enabled home

2.2 Actual V2H Setup: A Real-World Residential Integration for Backup Power Using the Ford F-150 Lightning

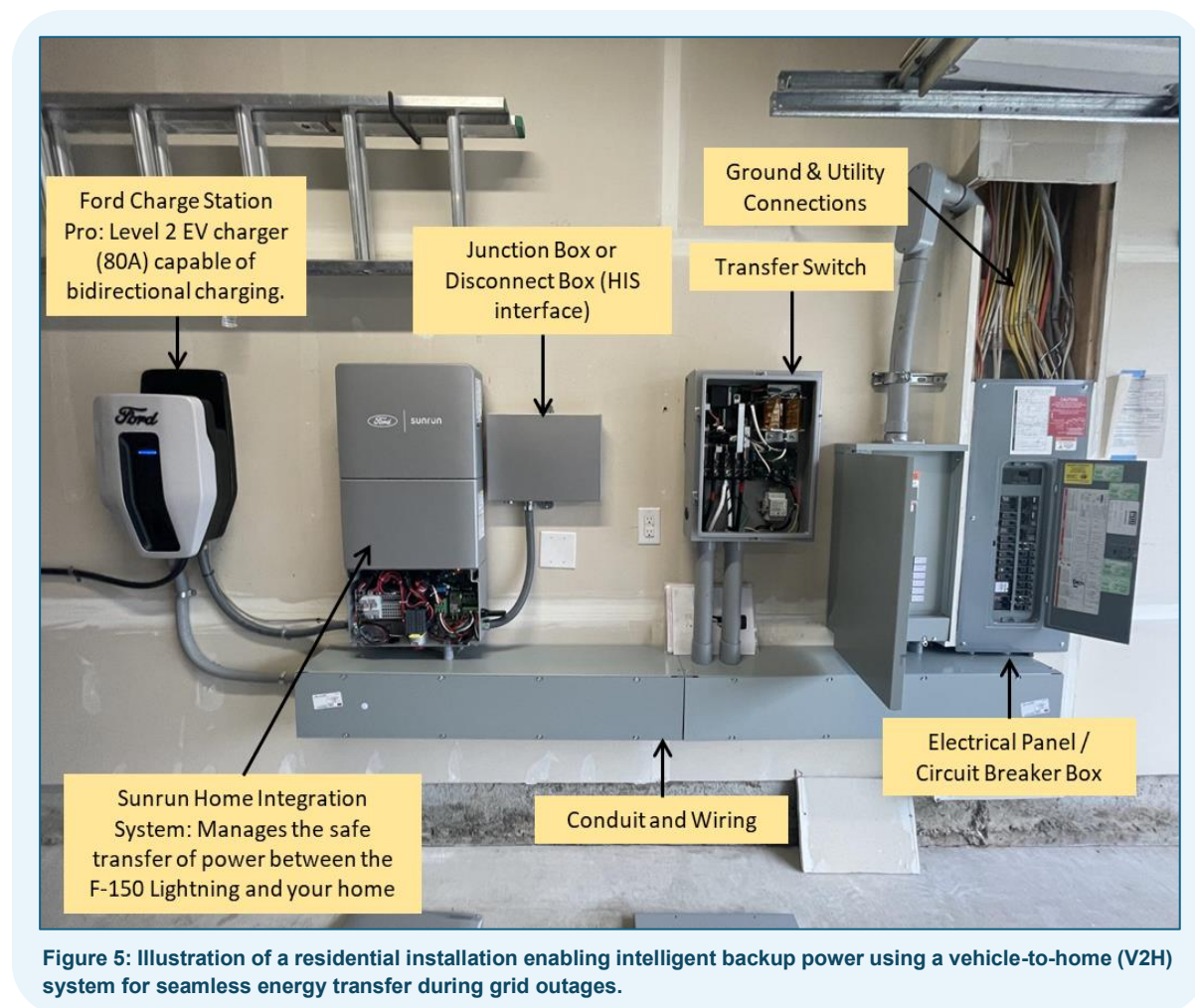
This section presents a general overview of a V2H system setup using key components such as a bidirectional EV charger, a home integration system (HIS), an automatic transfer switch, a backup load panel, and the main electrical panel.

In this configuration, the Ford Charge Station Pro enables both charging and discharging of the vehicle. The Home Integration System coordinates power transfer between the grid, the home, and the vehicle.

During a power outage, the transfer switch isolates the home from the grid and routes power from the vehicle to critical loads through a dedicated backup panel. Conduits and wiring ensure secure electrical connections between components, while grounding and utility links maintain safety and compliance.

This real-world setup demonstrates how V2H systems can provide reliable backup power and support energy independence at

the residential level². The detailed wiring diagram of Ford V2H System Integration is given in Appendix C.



2.3 Utility Approval Process for V2H Systems: Insights from Japan

Japan is one of the countries where V2H is commercially available.

In Japan, the interconnection of V2H systems with the residential electricity grid is administered by regional electric utilities, most notably Tokyo Electric Power

Company (TEPCO), the primary distribution utility for the Kanto region. The interconnection approval process for V2H systems under TEPCO follows a structured sequence of steps, including:

- **Submission of pre-application documentation,**
- **Technical compatibility review,**
- **Execution of interconnection and supply contract amendments,**
- **Deployment or configuration of a bidirectional smart meter,**
- **Final operational authorization.**

² yed19. "Installing a Home Integration System for Intelligent Backup Power (without SunRun)." F-150 Lightning Forum. [Link](#)

Residential applicants are required to submit detailed technical documentation, such as certified equipment specifications (e.g., CHAdeMO-compliant bidirectional chargers), single-line wiring diagrams, protection settings, and proof of compliance via JET (Japan Electrical Safety & Environment Technology Laboratories) certification. TEPCO evaluates the system's anti-islanding performance, voltage/frequency protection, and the potential for reverse power flow.

Upon successful review, a certified smart meter capable of bidirectional measurement is installed or updated, and formal permission to operate the V2H system in grid-parallel mode is granted. This regulatory framework ensures safe,

standards-compliant integration of V2H systems without compromising grid stability or end-user safety^{3,4}.

2.3.1 Stage 1: Pre-Application Documentation

The interconnection process begins with the submission of technical and administrative documentation via TEPCO's online application portal or through a licensed electrical contractor authorized to coordinate distributed energy connections.

The documentation must confirm the technical integrity, certification status, and intended operation of the V2H system. The following materials are typically required for low-voltage residential applications³:

Table 2: Documentation required for low-voltage residential applications

Documentation required for low-voltage residential applications		
Document	Description	Format
Electricity Usage Application	Declares intent to connect a self-generation device (including V2H) to the TEPCO grid	TEPCO-standard application form (submitted via installer)
System Specification Sheet	Includes EVSE model, rated power (kW), DC interface type (e.g., CHAdeMO), and protection settings	Manufacturer's official datasheet
Single-Line Wiring Diagram	Illustrates system topology, including grid interconnection point, protective devices, and circuit layout	CAD or PDF format, signed/stamped by a licensed electrician
JET Certification Proof	Confirms compliance with Japanese technical standards for anti-islanding, insulation, and grid safety	JET certificate + default factory parameter sheet
Installation Confirmation Form	Optional but recommended in some cases; certifies installation by a qualified technician	TEPCO-approved installer declaration or stamp

³ Tokyo Electric Power Company. Guidance on Application Documents for Grid Interconnection from Private Power Generation Equipment. March 2016. [Link](#)

⁴ Yamazaki, Mitsuhiro, and Osamu Ikki. National Survey Report of PV Power Applications in Japan 2019. IEA Photovoltaic Power Systems Programme, October 2020. [Link](#)

2.3.2 Stage 2: Pre-Application Documentation

Once the required documentation is submitted, TEPCO Power Grid conducts a comprehensive technical review to assess the safety, compliance, and grid compatibility of the proposed V2H system. TEPCO verifies system compatibility³:

- **Grid Capacity Assessment:**

TEPCO evaluates the capacity of the local distribution transformer and feeder to handle potential reverse power flow without overloading the infrastructure.

- **Anti-Islanding Protection Verification:**

The system's protection functions, particularly anti-islanding, must comply with METI regulations and the JEM 1498 standard. Devices certified by JET are pre-validated to disconnect within the required threshold (≤ 2 seconds) upon grid outage.

- **Protection Parameter Validation:**

Submitted trip settings and relay configurations are reviewed to ensure compliance with TEPCO's protection guidelines for voltage, frequency, and insulation coordination.

- **Certification Verification:**

TEPCO confirms the authenticity and scope of the submitted JET certificate, ensuring that the exact make and model of the V2H charger is listed and that the installation matches certified specifications.

2.3.3 Stage 3: Commercial Agreement

Upon completion of the technical review, the applicant must formalize the interconnection through a series of contractual steps with TEPCO. This begins with the execution of a

grid interconnection agreement, which defines the operational terms, safety responsibilities, and compliance requirements for the V2H system operating in parallel with the distribution grid.

The agreement must be signed by the applicant, affixed with their registered seal, and accompanied by a revenue stamp in accordance with Japan's Stamp Duty Act. If the V2H system is configured to allow reverse power flow, such as exporting surplus energy to the grid, an amendment to the existing electricity supply contract is required to authorize bidirectional energy exchange.

In such cases, TEPCO may also initiate a separate power purchase agreement to define export conditions, compensation mechanisms, and billing reconciliation. Additionally, the agreement includes consent for installation or activation of a bidirectional smart meter capable of recording both consumption and export. These commercial agreements collectively establish the legal framework necessary for safe, regulated, and revenue-compliant V2H operation within TEPCO's distribution network³.

2.3.4 Stage 4: Metering and Installation

Following contract execution, TEPCO initiates the deployment or configuration of a bidirectional smart meter capable of recording both energy consumption and export. In most cases, TEPCO installs a standardized smart meter, pre-configured for reverse power measurement at the customer's premises. This meter is mounted at the point of common coupling (PCC), sealed with a unique identification number, and registered in TEPCO's asset management system. If the customer already has a compatible smart meter, only reconfiguration may be required.

Concurrently, the V2H system must be installed in accordance with the approved single-line diagram, ensuring full compliance with protective settings, grounding schemes, and communication protocols. Only certified V2H units with validated JET approval are permitted, and installation must adhere to the default factory-set parameters associated with the certification³.

2.3.5 Stage 5: Inspection and Final Permission

Once metering and installation are complete, TEPCO performs a final administrative validation to authorize system operation. For certified residential V2H systems, this typically does not involve a formal on-site inspection by TEPCO engineers; instead, compliance is verified through submitted documentation, installation reports, and, if applicable, visual confirmation during meter setup. The

system's configuration is checked against the approved design to ensure that certified equipment, protective settings, and anti-islanding functions are properly implemented. Upon satisfactory validation, TEPCO grants operational authorization by updating the customer's interconnection status within its internal systems. No separate physical certificate is issued; the signed contract and utility's internal approval serve as legal permission to operate the V2H system in grid-parallel mode.

At this point, the homeowner may safely begin V2H operations, enabling bidirectional energy flow between the EV, home, and grid in accordance with TEPCO's regulatory and technical standards³. In the Indian context, while standardized procedures for residential V2H grid interconnection are yet to be fully established, the multi-stage approval process adopted by Japanese utilities like TEPCO can serve as a valuable reference model.

3. Power Flow Control and Optimization

Effective V2H operation relies on intelligent coordination of power flows between the EV, household loads, and the grid to minimize electricity costs, preserve battery health, and maintain user comfort. Depending on the system's complexity and available forecasts, different control strategies are adopted—ranging from simple rule-based scheduling to more advanced optimization techniques like Linear Programming (LP) and Model Predictive Control (MPC). Table 3 summarizes these commonly used approaches, outlining their operational logic and mathematical formulations. These control logics are typically embedded within Home Energy Management Systems (HEMS) or Central Management Systems (CMS), which govern the V2H operation. A well-designed HEMS will already have

these control strategies in place. Users are only required to provide basic inputs such as energy price preferences, battery SoC limits, usage schedule, and backup requirements for the system to function effectively. While these represent standard methods in current V2H applications, this is not an exhaustive list; other control logics such as stochastic, fuzzy, or learning-based models are actively being explored in ongoing research. Figure 10 shows a typical architecture of a home energy management system (HEMS) interface where the gateway coordinates real time data exchange between electric vehicles, solar PV, energy storage, smart appliances, and external cloud and grid entities, integrating tariff signals, user preferences, and weather forecasts for optimized V2H control⁵.

Table 3: Control Strategies of V2H Operation

Control Strategies of V2H Operation		
	Description	Mathematics
Rule-Based Optimization (Tariff-Aware Scheduling)⁶	Uses predefined energy price bands (day/night/peak) and EV SoC limits to control charge/discharge timing. V2H is activated during peak prices if SoC is above threshold; charging is done at night	Tariff Structure: Night: 00:00-08:00 Peak: 17:00-19:00 Day: All other times SoC Limits: $0.3E_{max} \leq E(t) \leq 0.8E_{max}$ $E(t = 7:00) \geq 0.7E_{max}$ (daily departure constraint) Charging (Night Hours): If $t \in [00:00, 08:00] \Rightarrow$ $P_{EV \leftarrow Grid}(t) = \min(P_{cap}, E_{max} - E(t))$

⁵ S&P Global Commodity Insights. "Energy Management Systems Key to Helping Residential Customers Navigate Increasingly Complex Energy Markets." pv magazine, March 13, 2025. [Link](#)

⁶ Zhang, Shuo, Suzanne Byrne, Liam Fennelly, and Seán Lyons. "Home Energy Optimization Using Vehicle-to-Home." Open Research Europe 5 (2025): 48. [Link](#)

Control Strategies of V2H Operation

	Description	Mathematics
Rule-Based Optimization (Tariff-Aware Scheduling)⁶		Discharging Rule (Peak Time): If $t \in [17:00, 19:00]$ and $E(t) \geq 0.3E_{max} \Rightarrow$ $P_{EV \rightarrow Home}(t) = \min(P_{cap}, D(t))$ $E(t)$: SoC at time t E_{max}: EV battery capacity (57.5 kWh) P_{cap}: Max charge power (7.2 kW) $D(t)$: Household demand η: Charger efficiency (e.g., 90%) Δt: Time step (e.g., 1 hour)
Linear Programming (LP)⁷	Optimizes household electricity cost using bidirectional V2H operation by shifting EV discharge to high-tariff hours and charging to low-tariff hours, ensuring SoC and power constraints are met.	Objective: $\min \sum C_t (E_t^{house} + E_t^{EV,cha})$ Power balance: $\eta_{dis} E_t^{EV,dis} \leq E_t^{house,dem}$ Charge/ discharge limits: $E_t^{EV,cha} \leq P_{cha} \tau_t, E_t^{EV,dis} \leq P_{dis} \tau_t (1 - z_t)$ SoC Constraints: $SoC_{min} \leq SoC_t \leq SoC_{max}, SoC_T = SoC_{max}$ Binary Constraint: $z_t \in \{0,1\}$
Model Predictive Control (MPC)⁸	Forecast-based control that minimizes electricity cost and SoC fluctuations over a prediction horizon while respecting system constraints in a V2H setup.	Objective: $\min \left[w_1 \sum C_t P_t^{grid} - w_2 \sum C_t P_t^{export} + w_3 \sum \Delta SoC_{EV} + w_4 \sum \Delta SoC_B + w_5 \sum (T_{op} - T_{bound})^2 + w_6 \sum T_{op} - T_{set} \right]$ SoC bounds: $0.3 \leq SoC_t^{EV} \leq 0.9$ Power flow: EV ↔ Grid, EV ↔ Home, EV ↔ Battery HVAC temperature limits: $T_{op}^i \in [T_{lb}^i, T_{ub}^i]$ P_{grid}: Grid Import Power P_{export}: Grid Export Power SoC_{EV}: EV Battery SoC SoC_B: Home Battery SoC T_{op}: Indoor Room Temperature T_{bound}: Comfort Temperature Limit T_{set}: Desired Set Temperature $w_1 \dots w_6$: MPC Cost Weights

⁷ Seal, Sayani, Debraj Chakraborty, Saikat Sinha, and Aurobinda Routray. "Centralized MPC for Home Energy Management With EV as Mobile Energy Storage Unit." IEEE Transactions on Sustainable Energy 14, no. 3 (2023): 1996–2007. [Link](#)

⁸ Einolander, Johannes, Annamari Kiviaho, and Risto Lahdelma. "Household Electricity Cost Optimization with Vehicle-to-Home Technology and Mixed-Integer Linear Programming." In 2023 International Conference on Future Energy Solutions (FES), 1–5. IEEE, 2023. [Link](#)

Data flow of home energy systems

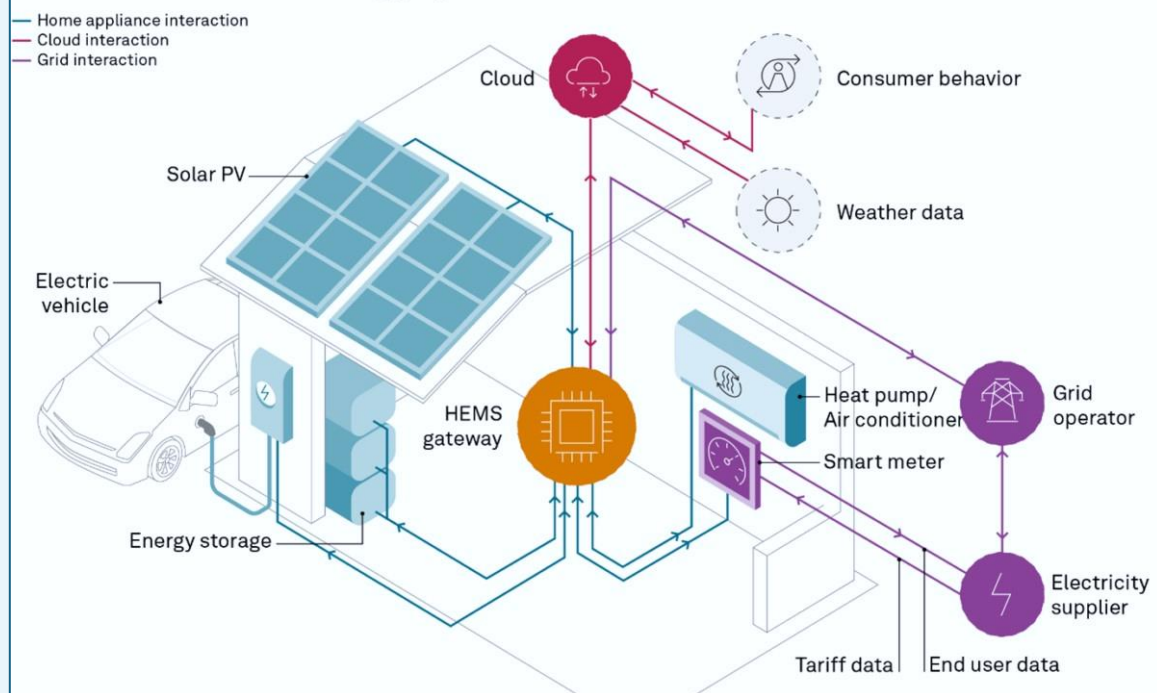


Figure 6: A typical architecture of Home Energy Management System (HEMS)⁵

4. Power Quality and Stability Observations in V2H Systems

V2H systems play a pivotal role in enhancing residential energy flexibility by enabling bidirectional power exchange, supporting backup power functionality during grid outages, and facilitating intelligent energy management strategies that improve overall system resilience and operational efficiency. As they enable bidirectional power flow between the EV and home through power electronic converters, it becomes important to address and optimize certain power quality aspects.

These include managing voltage imbalance, harmonics, flicker, and potential network loading, each of which, when understood and mitigated properly, opens opportunities for improved system design. For instance, while single-phase V2H chargers can introduce phase imbalance in three-phase systems, with some studies noting Voltage Unbalance Factors (VUF) up to 20%, this insight has guided more adaptive converter designs to maintain DC bus stability and minimize battery current oscillations (± 100 A). Harmonics of the 3rd, 5th, and 7th orders

can emerge during both charging and discharging operations, especially under low-output scenarios and PV coupling; however, these are well-characterized and manageable through filtering strategies and smart control.

Encouragingly, advanced techniques like Model Predictive Control (MPC) have demonstrated excellent results, bringing grid current THD in V2G mode to below 1.5 percent. Similarly, while rapid power variations may lead to flicker in certain grid contexts, standards like IEC 61000 provide measurable thresholds ($P_{st} > 1.0$) to ensure system compliance. Dynamic load shifts can cause interharmonics and voltage sags or swells, but modern converter systems are increasingly equipped to handle these efficiently, preserving both power quality and battery health. Table 4 summarizes these key power quality considerations, associated measurements, and standards, offering a comprehensive guide for designing robust V2H-enabled smart grid systems.

Table 4: Observed Impacts of V2H Operation

Observed Impacts of V2H Operation			
	Observed Impact in V2H Systems	Measurement Techniques	Relevant Standards/ Guidelines
EV-Induced Harmonics (3rd, 5th, 7th Order)⁹	Harmonics from EV chargers (notably 3rd, 5th, 7th) distort voltage waveforms and raise THD. The 3rd harmonic accumulates in the neutral,	Spectrum analysis via FFT; real-time harmonic monitoring using Yokogawa	IEEE 519-2022, IEC 61000-3-2

⁹ Guo, Jingli, Jin Yang, Preye Ivry, and Clara Serrano. "Analysis of the Impacts of V2G Chargers on LV Grid Harmonics." In 2020 9th International Conference on Renewable Energy Research and Applications (ICRERA), 88–92. Glasgow, UK: IEEE, 2020.

Observed Impacts of V2H Operation

	Observed Impact in V2H Systems	Measurement Techniques	Relevant Standards/ Guidelines
EV-Induced Harmonics (3rd, 5th, 7th Order)⁹	risking overheating. When multiple chargers operate simultaneously, harmonic summation can amplify distortion beyond limits.	WT1803E or equivalent; harmonic summation index (HSI) as proposed in lab studies.	
Total Harmonic Distortion (THD)-G2V (Charging)¹⁰	During G2V operation, voltage THD at the PCC increased from 3.01% (baseline, no EVCS) to 5.23% when EVCS operated at low output power, and to 4.03% at high output power. As per EN 50160:2010, "Under normal operating conditions, the total THD of the supply voltage shall not exceed 8% of the fundamental frequency." While the PCC remained within this threshold, in Scenario C (low EVCS output + PV injection), end-of-feeder buses exceeded 8% THD, posing risks to power quality and equipment longevity. These findings underscore that low-power EV charging generates disproportionately higher harmonic distortion.	THD captured using power quality analyzers (per IEC 61000-4-x); harmonic load flow simulations conducted in DIgSILENT PowerFactory for multiple scenarios. THD evaluated at PCC and along all LV buses.	IEEE 519-2022; IEC 61000-4-7; EN 50160:2010
Total Harmonic Distortion (THD) – V2G (Discharging)¹¹	During discharging (V2G), grid current THD is reduced to <1.5%, and in some cases <1%, using advanced control techniques like Model Predictive Control (MPC) and Sliding Mode Control (SMC). These values comply with IEEE 519-2022, which recommends a current THD limit of ≤5% at the PCC for LV systems.	THD computed via simulation of SMC/MPC-controlled V2G converters; values reflect idealized system performance.	IEEE 519-2022 (current THD ≤5%); IEC 61000-4-7 (THD definition)
Flicker Index¹²	Rapid variations in charging or discharging power in V2H systems can cause short-term voltage fluctuations, leading to perceptible light flicker, especially in weak grids or with LED lighting. According to IEC 60050-161, flicker is the "impression of unsteadiness of visual sensation." To ensure user comfort and equipment	Assessed using flicker meters conforming to IEC 61000-4-15, which calculate short-term (P_{st} , 10 min) and long-term (P_{lt} , 2 hr) flicker severity indices. Evaluation involves signal processing of	IEC 61000-3-3:2013 (limits ≤16 A); IEC 61000-3-11 (conditional connection, >16 A);

¹⁰ Rusan, Marko, Krešimir Fekete, Zvonimir Klaić, and Kristijan Čvek. "Harmonic Impact of EV Charging Station on Prosumer-Rich Distribution Feeders." 2022 International Conference on Smart Systems and Technologies (SST), IEEE, 2022.

¹¹ Rana, Rahul, Tejinder Singh Saggu, Shimi Sudha Letha, and Farhad Ilahi Bakhsh. "V2G Based Bidirectional EV Charger Topologies and Its Control Techniques: A Review." Discover Applied Sciences 6, no. 588 (2024).

¹² Newtons 4th Ltd. "Electromagnetic Compatibility – IEC61000-3-3:2013 Flicker Analysis." Accessed May 23, 2025. [Link](#)

Observed Impacts of V2H Operation

	Observed Impact in V2H Systems	Measurement Techniques	Relevant Standards/Guidelines
Flicker Index¹²	compliance, limits of $P_{st} \leq 1.0$ (10 min) and $P_{lt} \leq 0.65$ (2 hr) must be maintained. Tests are conducted at Z_{ref} (a standardized source impedance per IEC 60725). For equipment rated above 16 A per phase, IEC 61000-3-11 applies.	half-period RMS voltage variations (Uhp) to model lamp response, with results benchmarked against the $P_{st} = 1$ perceptibility threshold curve defined in IEC 61000-3-3.	
Inter-harmonics¹³	Caused by unbalanced loading and inverter control interactions, interharmonics (e.g., 104 Hz, 117 Hz, 134 Hz) in V2G systems distort voltage waveforms and risk control instability and harmonic resonance.	Quantified via FFT-based spectral analysis using interharmonic subgroups as per IEC 61000-4-7; mitigated through frequency-selective virtual impedance control.	IEEE Std 519-2022; IEC 61000-4-7
Voltage Sag/Swell¹⁴	Voltage sags of 15–30% in G2V mode cause DC bus overshoots up to ~600 V and battery current spikes during transient recovery. V2H load steps of 2–5 kW introduces surge currents that stress converter controls. These events pose thermal and aging risks to the battery and highlight the need for robust converter protection.	Measured as RMS voltage deviation per IEC 61000-4-30; sag or swell magnitude (e.g., >10%) and duration (e.g., 0.05–1 s) are monitored at the PCC using standardized event capture. DC bus voltage deviations are assessed separately through simulation or onboard measurement to evaluate converter stress response.	IEC 61000-4-30; IEEE Std 1159-2019; EN 50160
Voltage Unbalance	Single-phase V2H chargers introduce uneven loading across phases in three-phase distribution networks. In G2V mode, simulations by Guo et al. show that a 20% Voltage Unbalance Factor (VUF) leads to DC bus instability and battery current oscillations up to ± 100 A, increasing thermal and electrochemical stress. In V2H mode, dynamic load changes further heighten the system's sensitivity to such asymmetries.	Calculated using the Voltage Unbalance Factor (VUF), the ratio of negative to positive sequence voltage components. Voltage unbalance is measured per IEC 61000-4-30 at PCC using RMS-based analysis; additional DC bus effects are assessed via converter-side simulation or high-speed logging.	IEC 61000-4-30 (voltage unbalance measurement); IEEE Std 1159-2019 (event classification, disturbance definitions); NEMA MG-1-2016 (motor derating, performance under voltage unbalance)

¹³ Çelik, M. E., and R. M. Meral. "A Coordinated Virtual Impedance Control Scheme for Three Phase Four Leg Inverters of Electric Vehicle to Grid (V2G)." *Energy* 246 (2022): 123354.

¹⁴ Guo, Xiaoqiang, Jian Li, and Xiaoyu Wang. "Impact of Grid and Load Disturbances on Electric Vehicle Battery in G2V, V2G, and V2H Mode." In *Proceedings of the 2015 IEEE Energy Conversion Congress and Exposition (ECCE)*, 5406–5410. IEEE, 2015.

4.1 Instrumentation, Monitoring, and Smart Diagnostics Framework

Reliable V2H operation depends on accurate measurement, continuous monitoring, and timely diagnostics, all of which are supported by a coordinated set of tools and systems.

As summarized in Table 5, key instrumentation includes power analyzers, smart meters, and phasor measurement units to capture detailed electrical behaviour and system events. Monitoring components like the Home Energy Management System (HEMS) and Battery Management System (BMS) track energy usage and battery status in real time, while cloud-connected EVSE platforms enable remote supervision

Table 5: Instrumentation, Monitoring, and Smart Diagnostics Framework

Instrumentation, Monitoring, and Smart Diagnostics Framework		
	Component/ Tool	Operational Role
Instrumentation	Precision Power Analyzers	Acquires high-fidelity voltage and current waveforms at sub-cycle resolution; supports harmonic decomposition and transient analysis.
	Digital Signal Oscilloscopes (DSO)	Records transient waveforms and electrical noise; supports real-time comparison and spectral (FFT) diagnostics
	Smart Energy Meters (Class 0.2s or better)	Monitors power, voltage, frequency with high accuracy; incorporates edge analytics for localized insights
	Phasor Measurement Units (μ PMUs)	Provides time-synchronized phasor (V, I) data; facilitates grid event correlation and real-time disturbance diagnostics
Monitoring	Home Energy Management Systems	Tracks home load-EV interaction; enables dynamic scheduling and load disaggregation
	Battery Management System Telemetry	Continuously reports State of Charge (SoC), State of Health (SoH), cell temperatures, and voltage balancing; supports prognostic health monitoring
	EVSE Cloud Backends (via OCPP 2.0.1)	Monitors charging sessions and faults remotely
Diagnostics	Harmonic Distortion Analyzers	Quantifies THD and individual harmonic; supports IEEE 519/EN 50160 compliance checks
	Rate-of-Change Error Detectors (RoC)	Identifies dynamic anomalies like mismatch, delay, overshoot; enables early fault detection during transitions
	Event Loggers with Time-Tagging (<1 ms)	Records fault events with high-resolution timestamps; supports root-cause analysis and synchronization with external system logs

and fault reporting. Diagnostic tools such as harmonic analyzers, rate-of-change detectors, and event loggers help identify power quality issues and operational anomalies, ensuring safe, efficient, and compliant V2H performance.

A typical residential V2H setup does not require an extensive array of monitoring and diagnostic tools. While advanced instruments are useful in pilot projects, demonstrations, or grid integration studies, most homes can operate effectively with just a V2H-capable charger, a smart meter, and a well-integrated HEMS.

4.2 Case Studies and Pilot Deployment of V2H

Several real-world case studies and pilot deployments have demonstrated the technical and economic potential of V2H systems across different regions and use cases. As summarized in Table 7, these projects vary in scale, objectives, and configurations but collectively highlight the growing interest in leveraging EV batteries as flexible home energy resources.

Notable examples include the PG&E–GM pilot in California, which validated the

residential backup capability and cost-saving benefits of GM's bidirectional V2H bundle, and the Volkswagen pilot in Sweden, which utilized software-enabled V2H integration with solar PV in ID. series EVs. The Ford–Resideo simulation explored coordinated EV-HVAC energy use, while the Piha trial in New Zealand assessed V2H for rural backup and peak shaving. Other initiatives, such as the Mitsubishi i-MiEV post-disaster application and Australia's PV-storage integration studies, showcased V2H's role in resilience and grid independence.

Emerging deployments in India (IIT Bombay), Germany (Audi-Hager), and the U.S. (Sunrun-BGE) further demonstrate that, despite limitations like hardware compatibility, regulatory uncertainty, and small pilot scales, V2H is maturing into a viable tool for enhancing energy flexibility, promoting renewable integration, and supporting household-level grid services.

4.2.1 Commercial V2H Products: EVs and Bidirectional Chargers

Table 6 summarizes the key features of several commercial V2H products.

Table 6: Commercial V2H Products¹⁵

Commercial V2H Products		
	Bus Type	Bus Type
Nissan	LEAF + Nissan Energy Share / Energy Home ¹⁶	Factory-supported CHAdeMO V2H/V2G using Energy Share platform; optimized for backup, solar self consumption, and energy management.
Ford	F 150 Lightning + Charge Station Pro + Home Integration System (Sunrun™) ¹⁷	Level 2 bidirectional charger + inverter enabling home backup/outage power; backup kit priced \$3,895 excl. install

¹⁵ It should be noted here that all these V2H systems are not interoperable and only work with the products and vehicles they come with.

¹⁶ Nissan Motor Co., Ltd. "Factsheet: Nissan LEAF Vehicle-to-Home (V2H)." PDF. Nissan Asia, 2021. [Link](#)

¹⁷ Sunrun. 2025. "Ford F-150 Lightning Home Integration System." [Link](#)

Commercial V2H Products

	Bus Type	Bus Type
GM	GM Energy V2H Bundle (PowerShift Charger + Enablement Kit + Home Hub + Inverter + Dark Start battery) ¹⁸	19.2 kW charger; up to 9.6 kW discharge; UPS-like home backup; part of PG&E pilot; total system cost \$7,300-\$12,700 ¹⁹
Wallbox	Quasar 2 DC Bidirectional Charger (+ Power Recovery Unit) ²⁰	CCS bidirectional: 11–12 kW charging/discharging; enables 3 days home backup, solar charging, dynamic load management.
Fermata Energy	FE 20 / FE 15 Bidirectional Charger (CHAdEMO V2X) ²¹	UL 9741 & UL 1741-SA certified ²² ; approved by Nissan for LEAF use; V2X platform for stationery and grid services
Hyundai Kai	Ioniq 5/6, EV6, EV9 + compatible bidirectional chargers (Wallbox Quasar 2, Ambibox/Hungary,	V2L active; V2H/V2G under pilot/testing; Ioniq spacecraft shows discharge of EV at 4 kW in trials; EV9 confirmed hardware compatibility via Quasar 2
Ambibox GmbH	Ambibox DC Bidirectional Wall box ²⁴ Charger	11–22 kW DC bidirectional; AC & solar integration

4.2.2. Case Studies and Pilot Deployment of V2H

Table 7 gives an extensive summary of V2H case studies and pilot deployments around the world.

Table 7: Case Studies and Pilot Deployment of V2H

Case Studies and Pilot Deployment of V2H					
	Objective	System Configuration	Project Summary	Conclusion	Limitation
PG&E–GM V2H Pilot (Mar 2022–Ongoing, expanded Mar 2025)²⁵	Deploy and scale V2H capability for residential backup and grid support using GM EVs	GM PowerShift 19.2 kW bidirectional charger + GM Energy V2H Bundle; software-based energy coordination; compatible with 2024–25 Silverado, Equinox, Blazer,	Pilot launched in Mar 2022 with lab testing and limited trials. Expanded in Mar 2025 via GM Energy with customer rollout. Incentives up to \$4,500 per customer (base: \$2,500 + up to \$2,000	Validated technical and economic feasibility of V2H. EVs shown to enhance home energy resilience and grid flexibility. Demonstrates cost-	Concerns over battery warranty impacts, consumer hesitation to export power,

¹⁸ General Motors. 2025. "GM Energy V2H Bundle: Comprehensive Home Energy Solutions." GM Energy. [Link](#)

¹⁹ Rohde, Thomas. 2024. "GM EV Home Charging Products Compared." GM Authority, May. [Link](#)

²⁰ Wallbox. n.d. "Quasar 2 – V2H & V2G Bidirectional EV Charger." [Link](#)

²¹ Fermata Energy. 2024. "Nissan Approves Enhanced Fermata Energy FE-20 Bidirectional Charger and V2X Platform for Use with Nissan LEAF." August 28, 2024.

²² UL Solutions. 2023. "UL Solutions Issues First Certification to UL 9741 and UL 1741 SA for an AI-Driven Vehicle-to-Grid Compliant EV Charger to Fermata Energy." Press release, October 11, 2023.

²³ Thai, Danny. 2024. "Hyundai Ioniq 5 Bidirectional Charging Successfully Trialied." Zecar, September 1, 2024. [Link](#)

²⁴ Ambibox GmbH. 2023. "ambiCHARGE: Bidirectional DC Charging Technology." Ambibox GmbH. [Link](#)

²⁵ GM News. GM Energy and PG&E Collaborate to Pilot Vehicle-to-Home Electric Vehicle Charging Technology. March 13, 2025. [Link](#)

Case Studies and Pilot Deployment of V2H

	Objective	System Configuration	Project Summary	Conclusion	Limitation
PG&E–GM V2H Pilot (Mar 2022–Ongoing, expanded Mar 2025)²⁵		Sierra Denali, Cadillac Lyriq; integrated with PG&E's grid and customer EMS	for priority groups). V2H bundle market price: \$7,299. Customers must enroll in PG&E's Emergency Load Reduction Program. GM plans >1 million EVs by 2025, representing 50–100 TWh of potential energy storage.	saving potential and climate resilience benefits.	and policy/regulatory barriers. Limited to California. Requires customer participation and compatible EV models.
Ford–Resideo V2H Pilot (Dec 2023 – H1 2024)²⁶	Evaluate how coordinated V2H energy use + smart thermostat can reduce bills and support grid	Ford F-150 Lightning with Intelligent Backup Power + Resideo Smart Thermostat; bidirectional EV-HVAC link	Simulation started Dec 2023, ends H1 2024. Uses F-150 Lightning battery to power HVAC via smart thermostat. Targets: monthly bill savings, TOU load shift, grid relief, and clean energy use. First such OEM-HVAC V2H project.	Coordinated EV and thermostat use may enhance energy efficiency, comfort, and grid resiliency through smart scheduling of HVAC loads using EV battery.	Simulation only; not deployed in homes yet. Effectiveness depends on TOU tariff, household behaviour, grid availability of renewables.
Volkswagen V2H Pilot – Sweden (Dec 2023 – Ongoing)²⁷	Deploy V2H in ID. models via software to support home energy needs and integrate with solar PV	VW ID. models with 77 kWh battery, upgraded to ID. Software 3.5; compatible only with HagerEnergy S10 E COMPACT DC home power station; ISO 15118-2 standard	Announced Dec 2023. Vehicles become V2H-capable via software update. Active pilot in Stenberg housing estate, Hudiksvall, Sweden. Vehicles support ~30 kWh/day household load (~2 days backup) with >20% SoC reserve. Integration with PV and HEMS enables storage of solar energy and grid-friendly load shifting.	Converts EVs into smart energy storage. Allows solar energy self-use, bill savings, and support for grid balancing. A pioneering implementation using CCS-based DC V2H.	Limited hardware compatibility (HagerEnergy S10 E COMPACT only); region-specific rollout; incompatible with AC systems; requires ID. Software 3.5+ update.
Piha V2H Trial – New Zealand (Sep 2019 – Ongoing)²⁸	Evaluate V2H for reducing peak demand and providing short-term backup in rural communities	Nissan Leaf + Smart DC Charger + V2H Unit at participant homes (individual setup)	Launched Sep 2019 in Piha, New Zealand. Run by Vector Ltd, co-funded by EECA under the Low Emission Vehicles Contestable Fund. Each participant uses V2H setup for ~1 month. Covers 2 homes. Aimed at backup supply during outages, peak shaving, household load management	Shows potential of V2H for grid-constrained, remote areas. Provides local backup, reduces peak load, and improves user control over energy use.	Small-scale trial; only 2 chargers; limited to Nissan Leaf; short trial duration per user; real-world scalability not yet tested.

²⁶ Ford Motor Company. Ford and Resideo Launch 'EV-Home Power Partnership' Project Driving Vehicle-to-Home Energy Management Benefits for Customers. December 7, 2023. [Link](#)

²⁷ Volkswagen AG. "Cleverly Manage Your Own Electricity: First ID. Models Support Bidirectional Charging." Volkswagen Newsroom, December 10, 2023. [Link](#)

²⁸ Vector Ltd. "Trial of Vehicle-to-Home Technology Kicks off in Piha." Scoop Business, September 2, 2019. [Link](#).

Case Studies and Pilot Deployment of V2H

	Objective	System Configuration	Project Summary	Conclusion	Limitation
Mitsubishi i-MiEV V2H Case Study²⁹	Enable emergency power supply and showcase V2H via MiEV Power Box following 2011 earthquake	i-MiEV with 16 kWh Li-ion battery + MiEV Power Box (CHAdeMO-based AC output, 100V, max 1,500W); bidirectional V2H via DC-to-AC converter	Introduced post-2011 Great East Japan Earthquake. MiEV Power Box launched to allow i-MiEV to power appliances. Provides 1.5 kW AC output, enough for critical home loads (lighting, fridge, phone charging, etc.). Battery reserve: ~16 kWh. Global sales (i-MiEV + Minicab MiEV): ~31,000 units by Apr 2019. Used by Japan Post & for disaster response.	First OEM to deliver factory-supported V2H in a commercial EV. Helped validate disaster resilience, grid independence, and practical V2H through real-world use.	Limited output (1.5 kW); not suitable for full home backup; only supports CHAdeMO-compatible appliances; older battery chemistries with limited range and aging support.
V2H Integration with PV & Storage – Australia (2017–2020)³⁰	Optimize household energy use and reduce grid reliance using EV, solar PV, and storage bills and support grid	EV with V2H capability + Residential PV system + Battery Energy Storage (BES) + Home Energy Management System (HEMS)	Conducted by University of South Australia. Model simulated integration of EV, solar, and home storage. Showed up to 25% cost savings in public charging scenarios. Reduced grid dependence and delayed need for infrastructure upgrades. Controlled using dynamic pricing and TOU-aware HEMS.	Integration of V2H with solar and battery improves cost efficiency, self-sufficiency, and grid flexibility for residential energy systems.	Effectiveness varies by tariff design; depends on accurate energy forecasting and advanced HEMS; based on simulation, not live deployment.
IIT Bombay V2H & V2G Field Trial – India (2024 – Ongoing)³¹	Demonstrate practical V2H/V2G use for peak shaving, PV utilization, backup support, and net-zero grid exchange	EV with bidirectional charger, rooftop solar PV system, smart home loads, battery power, grid interface	Morning & evening peak shaving, islanding mode, and grid export enabled by EV.	The trial confirms V2H/V2G can support load shifting, PV utilization, and grid independence in urban Indian households with mixed charging scenarios.	Full seasonal/long-term performance under Indian grid conditions yet to be evaluated.

²⁹ "Mitsubishi Motors Celebrates a Decade of i-MiEV, Pioneering Mass-Production Electric Vehicles." Mitsubishi Motors Global Newsroom, June 5, 2019. [Link](#)

³⁰ Li, Nan, Mahdi Seyedmahmoudian, Saad Mekhilef, S.M. Mueen, and Ben Horan. "Vehicle-to-home operation and multi-location charging of electric vehicles for energy cost optimization of households with photovoltaic system and battery energy storage." *Renewable Energy* 219 (2023): 1197–1211.

³¹ "Vehicle to Home (V2H) and Vehicle to Grid (V2G) Field Demonstration." In *Proceedings of the National Workshop on Integrated Local Energy Systems*, October 9, 2024, pp.23-26

Case Studies and Pilot Deployment of V2H

	Objective	System Configuration	Project Summary	Conclusion	Limitation
Hager–Audi V2H Pilot – Germany (2020 – Ongoing)³²	Explore real-world use of bidirectional EV charging (V2H) to increase solar self-use and reduce grid reliance	Audi e-tron prototype, Hager E3/DC home power plant, Bidirectional DC wallbox, PV system integrated with smart energy control software	Started in 2020. Field test in single-family home using Audi EV + PV + Hager battery system. Focus on real-life use cases: storing self-generated solar energy in EV, discharging to home, improving user interface. Components include commercial home power plant with V2H interface, smart charging software, and a new DC wallbox.	Early results confirm EV batteries can serve as mobile energy storage, enhancing renewable energy use, self-sufficiency, and user energy control.	Limited to specific hardware (Audi + Hager E3/DC); data not fully yet published; real-world scalability and third-party interoperability under evaluation.
Sunrun–BGE V2H Pilot – Maryland, USA (Jun–Sep 2024)³³	Demonstrate V2H for backup power, peak load relief, and customer bill savings in U.S. homes	Ford F-150 Lightning (with Ford Charge Station Pro + Home Integration System), managed by Sunrun in partnership with BGE	First operational V2H “power plant” in the U.S. involving 3 customers with Ford F-150 Lightnings. Each truck discharged energy to the home during 5–9 p.m. weekday dispatch windows. EVs supplied home loads, reducing peak grid demand. Customers earned up to \$800 in payments over 4 months. Goal: prove V2H viability in real homes, with Sunrun as installer/operator and BGE as utility grid partner.	Demonstrated that V2H can provide real economic value and grid support with existing technology. A major U.S. proof-of-concept for residential bidirectional energy use.	Small-scale (3 customers); limited to specific hardware and region (Ford trucks + Sunrun + BGE); long-term scalability and integration with V2G remain under study.

³² Hager Group. “Hager Group Invests in Research Project on E-Mobility.” Hager Group – Technologies and Innovations, 2020.

[Link](#)

³³ Collins, Marybeth. “Sunrun and BGE Partner on First U.S. Vehicle-to-Home Power Plant.” Environment + Energy Leader, July 31, 2024. [Link](#)

5. Techno-Economic and Environmental Assessment of V2H

The techno-economic and environmental assessment of V2H systems evaluates their cost-effectiveness, energy savings, and emission reduction potential. By utilizing EV batteries for home energy needs, V2H can lower electricity bills and reduce peak demand charges. Integrating V2H with solar PV further enhances self-consumption and minimizes grid reliance.

Overall, V2H contributes to both household

resilience and decarbonization goals. These assessments are presented in detail in Table 8 and Table 9.

5.1 Economic Viability of Residential V2H Systems: NPV & Payback Period

Detailed description of economic viability of residential V2H systems is given in Table 8.

Table 8: Detailed description of economic viability of V2H

Economic Viability of V2H			
	NPV Estimate	Payback Period	Assumptions/ Notes
V2H with PV and Bidirectional Charger (Ireland)³⁴	₹46,507(€514) (under ₹5,43,000 capex)	~ 8 years	Three scenarios modelled with capital costs of: Low (₹271,500 (€3,000) @ 3% discount), Medium (₹5,99,100 (€6,000) @ 6% discount), High (₹9,98,500 (€10,000) @ 9% discount). At ₹5,99,100 (€6,000), NPV = ₹51,325.90 (€514); V2H becomes viable if investment ≤ ₹6,98,950 (€7,000). PV = 6 kW; EV = 57.5 kWh; charger = ₹1,49,775-₹7,48,875 (€1,500–7,500); HEMS = ₹2,795.80-₹55,916 (€28–€560); installation = ₹49,925-₹2,99,550 (€500–3,000)
Bidirectional Charging System (Jordan)³⁵	₹1,051,498 (\$12,589.94) (25-years)	~ 15-18 years	System: PV 4.5 kW, EV battery 10 kWh, Bidirectional charger: ₹742,368 (\$8,880); Time-of-Use (TOU) tariff applied; Simulation includes degradation, O&M, and dynamic energy pricing; Grid-connected rooftop solar household

³⁴ Zhang et al. (Ireland – V2H + PV + Bidirectional Charger) Zhang, Shuo, Terence O'Donnell, Sean Byrne, Liam Fennelly, Divyanshu Sood, and James O'Donnell. "Home Energy Optimization Using Vehicle-to-Home." Open Research Europe 5 (2025): 48.

³⁵ Bommana et al. (Jordan – Bidirectional Charging System) Bommana, Venkata, Malik Al-Amayreh, Ahmad Al Amayreh, and Bilal Khalaf. "Impact of EV Charging Strategies on Solar-Powered Residential Systems: Unidirectional vs. Bidirectional Charging in Jordan." Discover Sustainability 6 (2025): 407.

Economic Viability of V2H

	NPV Estimate	Payback Period	Assumptions/ Notes
PV + Battery + V2H with Efficiency Measures (Florida, USA)³⁶	Positive NPV achieved in Year 9 of 30-year analysis (for existing homes with PV + 42.2 kWh battery); V2H setup achieves savings earlier if charger cost < ₹501,600 (\$6,000)	~6–9 years for V2H setup (with ITC); PV-only systems reach positive cash flow sooner	Existing home: 9.5 kW PV, 42.2 kWh battery, V2H-capable EV (68.7 kWh); Bidirectional charger: ₹501,600 (\$6,000); Federal Investment Tax Credit (30%) applied; Savings up to ₹8,192.80 (\$98)/ month (solar EV driving); PV degradation: 0.5%/yr; Battery degradation: 3.5%/yr; 30-year analysis with 4.5% discount rate
V2H vs Stationary Battery (Japan)³⁷	Favourable when bidirectional charger cost is ≤ ₹108,600 (€1200) (i.e., one-third of current cost)	~9–10 years (only for non-commuter EV use case)	Scenario Year: 2030; PV: max 10 kW; Bidirectional charger cost tested at ₹3,59,46 (€3600), ₹2,39,640 (€2400), and ₹1,19,820 (€1200); Base EV battery: 40 kWh; EV use case: non-commuter allows higher V2H use; Environmental and cost benefits only appear if charger cost ≤ ₹1,19,820 (€1200); Compared with 15 kWh stationary battery; Model assumes perfect forecasting and MILP optimization
PV + EV System (UK)³⁸	₹127,800 (£1,200) in 2017 (down from ₹3,049,725 (£28,650) in 2011 for Brighton, 6 kW PV)	12–15 years (post-2016); much shorter before 2016 (e.g., ~6–7 years in 2011)	Locations: Fort William, Nottingham, Brighton; PV size: 6 kW; FIT reductions post-2012 significantly impact returns; EV as storage still unviable due to high charger + battery degradation costs; 50% generation assumed to be exported; discount rate: 2%; ESS improves NPV by 46% in Brighton

³⁶ Haggi and Fenton (Florida – PV + Battery + V2H) Haggi, Hamed, and James M. Fenton. “Techno-Economic Assessment of Net-Zero Energy Buildings: Financial Projections and Incentives for Achieving Energy Decarbonization Goals.” In IEEE Texas Power and Energy Conference (TPEC), 2025

³⁷ Kataoka et al. (Japan – V2H vs Stationary Battery)

Kataoka, Ryosuke, Hiroshi Asano, and Takayuki Kato. “Comparison of the Economic and Environmental Performance of V2H and Residential Stationary Battery: Development of a Multi-Objective Optimization Method for Homes of EV Owners.” World Electric Vehicle Journal 10, no. 4 (2019): 78.

³⁸ Wang et al. (UK – PV + EV System)

Wang, Yue, Patrick James, and Ronan Bolton. “Economic Evaluation of Photovoltaic and Energy Storage Technologies for Future Domestic Energy Systems.” Northumbria University Preprint, 2018.

5.1.1 Emission Metrics by System Configuration

Table 9 discusses the environmental assessment of V2H operation in detail.

Table 9: Environmental Assessment of V2H Operation

Environmental Assessment of V2H Operation		
	Estimated CO ₂ Reduction	Assumptions / Notes
V2H vs Conventional (Gasoline + Grid)³⁹	~35–42% CO ₂ reduction over a 35-year house + 11-year vehicle lifetime, based on full life cycle assessment.	Based on a life cycle inventory (LCI) comparing a V2H system (BEV, solar PV, and bidirectional charger) to a conventional setup with gasoline vehicle and petrol infrastructure in the Japanese context.
V2H + 100% Solar PV⁴⁰	Lifecycle emissions as low as 12–13 g CO ₂ /km or ~12–15 g CO ₂ eq/kWh when EV is exclusively charged by solar PV systems	Calculated under the assumption that the EV is charged entirely from rooftop solar PV, with no grid dependence. Stationary battery storage is not included in this estimate.
V2H + PV + Stationary Storage³⁶	Emissions significantly lower than grid-charged EVs	Emission reduction is based on the combined use of solar PV and home battery storage for EV charging. While no specific g CO ₂ eq/kWh value is reported, system performance is superior to grid-only setups.
V2H with High RE penetration (Hydro/Wind)³⁶	Estimated emissions of ~80–120 g CO ₂ eq/kWh when charged during periods of high renewable energy supply (e.g., hydro/wind mix)	Assumes EV charging is timed during periods of high renewable penetration (e.g., hydro/wind-rich grids such as Norway or Quebec). V2H discharging is modelled as household offset, not export to grid.
V2H with Time-of-Use Charging (No PV)⁴¹	Indirect CO ₂ savings from up to 30% shift in electricity cost and demand to off-peak hours; specific g CO ₂ eq/kWh not reported	Based on optimizing EV charging during low-tariff (and likely lower-emission) night hours and using the EV to power home during peak hours. Study focuses on cost, not explicit carbon intensity metrics.

³⁹ Kudoh, Yuki, Ryoko Motose, and Kiyotaka Tahara. "A Potential CO₂ Reduction of Vehicle to Home System from Life Cycle Perspective." In Proceedings of the 27th International Electric Vehicle Symposium (EVS27), Barcelona, Spain, November 2013

⁴⁰ Zhang, Shuo, and Gregory M.P. O'Hare. "Home Energy Optimization Using Vehicle-to-Home." Open Research Europe 5, no. 1 (2025): 1–15.

⁴¹ Sechilariu, Manuela, A. Reinders, Y. Krim, S. Cheikh-Mohamad, A. Sierra, G. Seiler, and K. Ben Slimane. PV-Powered Electric Vehicle Charging Stations: Preliminary Requirements and Feasibility Conditions. IEA PVPS Task 17 Report T17-02:2021. December 2021.

6. Interconnection Codes and Compliance

Integrating V2H systems with the power grid requires compliance with technical, safety, communication, and regulatory standards. Key standards like IEEE 1547-2018 and UL 1741 SA ensure safe grid interconnection and export control, while IEC 61851 and ISO 15118-20 govern charging and bidirectional communication.

Cybersecurity and EMI compliance are addressed by ISO/SAE 21434, IEC 62443, and CISPR 11. Accurate metering, grid communication, and energy resale legality also play vital roles. A detailed overview of these standards and their relevance to V2H systems is provided in Table 10.

Table 10: Interconnection Codes and Compliance

Interconnection Codes and Compliance		
	Standard / Code	Key Requirements & Relevance to V2H
Grid Interconnection	IEEE 1547-2018 ⁴²	Applies when the EV exports power to the grid (V2H2G mode). Must disconnect within 2 seconds during voltage/frequency anomalies. Supports ride-through for voltage dips down to 0.5 p.u. for 0.16 seconds. For 50 Hz systems, frequency-related functions need adaptation to local grid codes.
EV Charging Interface	IEC 61851-1 ⁴³	Defines EV and EVSE communication using PWM signals (duty cycle 3%–97%) to control charging current. Specifies Modes 1–4 for AC and DC charging. For bidirectional charging (V2H), IEC 61851-23 and IEC 61851-24 provide detailed requirements for DC charging systems and communication protocols.
Bidirectional Charger Safety	UL 9741, UL 1741 SA ^{44,45}	UL 9741 covers safety requirements for bidirectional EV charging system equipment, including functionality to export power from the EV to an electric power system. UL 1741 SA addresses inverters and other utility-interconnected distributed generation equipment for grid support functions, enabling smarter, safer reactive grid interconnection.

⁴² Institute of Electrical and Electronics Engineers. IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces. IEEE Std 1547-2018. New York: IEEE, 2018.

⁴³ International Electrotechnical Commission. Electric Vehicle Conductive Charging System – Part 1: General Requirements. IEC 61851-1. Geneva: IEC, 2017.

⁴⁴ Underwriters Laboratories. Standard for Electric Vehicle Power Export Equipment (EVPE). UL 9741. Northbrook, IL: UL, 2023.

⁴⁵ Underwriters Laboratories. Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources. UL 1741 SA. Northbrook, IL: UL, 2021.

Interconnection Codes and Compliance

	Standard / Code	Key Requirements & Relevance to V2H
Energy Resale Legality	Electricity Acts (India, USA, UK)	Energy resale from V2H systems is regulated by national electricity laws. In India, resale is generally restricted to licensed entities. In the USA and UK, it is permitted under specific programs such as net metering or Smart Export Guarantee, subject to utility and market rules.
Grid Communication Protocol	IEEE 2030.5 / SEP2.0 ⁴⁶	Enables secure communication between V2H systems, home energy managers, and utility platforms. Supports functions like real-time monitoring, demand response, and energy export control. Required for V2H systems participating in grid services under standards like California Rule 21.
Cybersecurity Framework	ISO/SAE 21434, IEC 62443 ^{47,48}	ISO/SAE 21434 ensures cybersecurity for vehicle-side V2H components, covering threat detection and secure communication. IEC 62443 applies to infrastructure components like chargers, HEMS, and utility interfaces, enforcing security across V2H networks. Together, they help protect V2H systems from cyber threats in both vehicle and grid environments.
EMI/EMC Compliance	CISPR 11 (EN 55011) ⁴⁹	Specifies limits for electromagnetic emissions from EV chargers and power electronics used in V2H systems. Class B limits typically apply to residential use, ensuring devices do not interfere with nearby electronics. Compliance is essential for certification and safe operation in domestic environments.
Power Quality Compliance	IEC 61000-3-2/3-12 ^{50,51}	These standards limit harmonic current emissions from V2H inverters to maintain grid power quality. IEC 61000-3-2 applies to equipment ≤16 A, while IEC 61000-3-12 covers 16–75 A systems. Compliance ensures the V2H system does not distort voltage or disrupt other devices on the local grid.
Metering Accuracy	IEC 62052 / 62053 ^{52,53}	The IEC 62052-11 standard outlines general requirements, tests, and conditions for electricity metering equipment, ensuring reliable performance under various environmental and electrical conditions. Complementing this, IEC 62053-21 and IEC 62053-22 specify accuracy

⁴⁶ Institute of Electrical and Electronics Engineers. IEEE Standard for Smart Energy Profile Application Protocol. IEEE Std 2030.5-2018. New York: IEEE, 2018.

⁴⁷ International Organization for Standardization and SAE International. Road Vehicles – Cybersecurity Engineering. ISO/SAE 21434:2021. Geneva: ISO, 2021.

⁴⁸ International Electrotechnical Commission. Industrial Communication Networks – Network and System Security – Part 1: Terminology, Concepts and Models. IEC 62443-1-1. Geneva: IEC, 2009.

⁴⁹ International Special Committee on Radio Interference. Industrial, Scientific and Medical Equipment – Radio-Frequency Disturbance Characteristics – Limits and Methods of Measurement. CISPR 11:2015. Geneva: IEC, 2015.

⁵⁰ International Electrotechnical Commission. Electromagnetic Compatibility (EMC) – Part 3-2: Limits – Limits for Harmonic Current Emissions (Equipment Input Current ≤16 A per Phase). IEC 61000-3-2. Geneva: IEC, 2018.

⁵¹ International Electrotechnical Commission. Electromagnetic Compatibility (EMC) – Part 3-12: Limits – Limits for Harmonic Currents Produced by Equipment Connected to Public Low-Voltage Systems with Input Current >16 A and ≤75 A per Phase. IEC 61000-3-12. Geneva: IEC, 2011.

⁵² International Electrotechnical Commission. Electricity Metering Equipment – General Requirements, Tests and Test Conditions – Part 11: Metering Equipment. IEC 62052-11. Geneva: IEC, 2020.

⁵³ International Electrotechnical Commission. Electricity Metering Equipment – Particular Requirements – Part 21: Static Meters for AC Active Energy (Classes 1 and 2). IEC 62053-21. Geneva: IEC, 2020.

Interconnection Codes and Compliance

	Standard / Code	Key Requirements & Relevance to V2H
Metering Accuracy		classes for active energy meters, such as Class 1.0 ($\pm 1\%$) and Class 0.5s ($\pm 0.5\%$), which are crucial for precise energy measurement
EV Communication Protocol	ISO 15118-20 ⁵⁴	ISO 15118-20 is the latest standard in the ISO 15118 series, enhancing communication between electric vehicles (EVs) and the electric vehicle supply equipment (EVSE). It introduces support for bidirectional power transfer, enabling functionalities like V2H, Vehicle-to-Grid (V2G), and Vehicle-to-Building (V2B). The standard also incorporates features such as Plug & Charge for seamless authentication and advanced scheduling capabilities for optimized energy usage.

6.1 Communication protocols and cybersecurity mechanisms

Secure and efficient V2H operation relies on robust communication protocols and cybersecurity measures. ISO 15118-20 enables bidirectional energy flow and Plug & Charge between EVs and chargers, while

OCPP 2.1 supports backend control, secure updates, and energy management. Within the home, EEBUS and Modbus facilitate coordination with HEMS and DERs. TLS 1.3 encryption and PKI ensure secure data exchange and authentication. Additional measures like intrusion detection and time synchronization (NTP) enhance system reliability. Table 11 summarizes these protocols and their roles in V2H systems.

Table 11: Communication and Cybersecurity Standard/Protocols with description

Communication and Cybersecurity Standard/ Protocols		
	Standard /Protocol	Functionality
EV ↔ Charger Communication	ISO 15118-20	Enables secure, bidirectional energy transfer and Plug & Charge functionality, crucial for seamless and automated V2H operation
Charger ↔ Backend⁵⁵	OCPP 2.1	OCPP 1.5 and 1.6 provide basic remote-control capabilities but lack the features needed for advanced V2H integration. OCPP 2.0 introduces support for ISO 15118 and includes device model abstraction, allowing better visibility and control of charger components. Building on this, OCPP 2.1 adds bidirectional charging capability

⁵⁴ International Organization for Standardization. Road Vehicles – Vehicle to Grid Communication Interface – Part 20: 2nd Generation Network Layer and Application Layer Requirements. ISO 15118-20:2022. Geneva: ISO, 2022.

⁵⁵ Open Charge Alliance. 2020. Open Charge Point Protocol 2.0.1 Specification. Arnhem, Netherlands: Open Charge Alliance. [Link](#)

Communication and Cybersecurity Standard/ Protocols

	Standard /Protocol	Functionality
Charger ↔ HEMS^{56,57}	Modbus / EEBUS	EEBUS enables secure and seamless energy coordination among EV, HEMS, and DERs. Modbus, while widely used, lacks semantic modeling and native cybersecurity, suitable for basic or legacy residential setups.
Communication Security⁵⁸	TLS 1.3 + PKI	Ensures encrypted data exchange and mutual authentication. Mandated in ISO 15118-20 to protect EV-charger communication from cyber threats such as spoofing or man-in-the-middle attacks.
Device Authentication⁵⁹	Plug & Charge (via ISO 15118)	Uses PKI-based mutual authentication between EV and charger. Certificates are managed via V2G Root CAs or OEM-issued sub-CAs (e.g., via Hubject). Simplifies user interaction and ensures trusted V2H participation.
Cybersecurity Monitoring⁶⁰	Local IDS / anomaly detection	Detects spoofing, unauthorized access, and abnormal system behaviour. Not yet standardized; currently applied in research pilots and advanced grid-integrated systems. Implementation can follow frameworks like IEC 62443 or NIST SP 800-82.
Time Synchronization⁶¹	NTP (residential)	NTP is suitable for log/event alignment and scheduling in V2H.

⁵⁶ EEBUS Initiative e.V. 2021. EEBUS Specifications Overview: Interoperability in Smart Energy Networks. Cologne: EEBUS. [Link](#)

⁵⁷ Modbus Organization. 2006. Modbus Application Protocol Specification V1.1b. Hopkinton, MA: Modbus Organization. [Link](#)

⁵⁸ National Institute of Standards and Technology (NIST). 2020. Guidelines for the Selection, Configuration, and Use of Transport Layer Security (TLS) Implementations. NIST SP 800-52 Revision 2. Gaithersburg, MD: U.S. Department of Commerce. [Link](#)

⁵⁹ Hubject GmbH. 2021. Plug & Charge Ecosystem Overview. Berlin: Hubject. [Link](#)

⁶⁰ Kour, Ravinder, Surender Soni, and Vinay Chamola. 2023. "Anomaly Detection in Electric Vehicle Infrastructure Using Machine Learning." Mathematics 13, no. 5: 712. [Link](#)

⁶¹ Mills, David L., et al. 2010. Network Time Protocol Version 4: Protocol and Algorithms Specification. RFC 5905. Internet Engineering Task Force (IETF). [Link](#)

7. Appendices

7.1 Appendix A: Technical Datasheets

Figure 11⁶² shows the technical datasheet of a sample V2H charger (10 kW, 208/240 Vac) from Delta Electronics (Americas), Ltd., which includes key specifications for both charging and discharging modes. It supports bidirectional operation with 96% peak efficiency in AC-DC and DC-AC

conversions, using the CHAdeMO interface. The charger handles input/output voltage ranges from 50 to 500 Vdc (DC side) and up to 45.5 A at 220 Vac (AC side), with a maximum power rating of 10 kW.

The unit is designed for reliable operation in harsh environmental conditions, offers multiple connectivity options (Ethernet, Wi-Fi, Bluetooth), and features a compact, IP55-rated wall-mounted design.

Charging Mode			Discharging Mode		
AC Side	Grid Connection Type	1P3W	DC Side	Rated Input Voltage	150 to 500Vdc
	Rated Input Voltage	208/240Vac		Max. Input Current	33.3A @ 300V
DC Side	Max. Output Power	10kW		Rated Input Power	10kW
	Output Voltage Range	50 to 500Vdc	AC Side	Rated Output Voltage Range	208/240Vac±15%
	Max. Output Current	33.3A @ 300V		Max. Current	45.5A @ 220Vac
AC to DC	Peak Efficiency	96%	DC to AC	Peak Efficiency	96%
Environmental			Mechanical		
Operating Temperature		-30°C to +50°C	Charging Interface		CHAdeMO
Cooling Method		Air Forced	Cable Length		4m straight cable
Relative Humidity		0 to 95%, non-condensing	Enclosure Rating		IP55 for outdoor wall-mounted
Operating Altitude		0 to 3000m	Net Weight		40kg
			Dimension (WxHxD)		500 x 790 x 200 mm
General					
User Interface		LED indicator (Alarm, Charge, Discharge), RFID authentication			
Network Connectivity		Ethernet (ECHONET LITE, OCPP 1.6), 4G/Wi-Fi/Bluetooth (Optional)			

Figure 7: Technical Specifications of V2H/V2G Charge (10kW/208/240Vac) from Delta Electronics (Americas), Ltd.

7.2 Appendix B: Results

The real-world observations recorded on April 9, 2024, as part of a demonstration by the Grid Integration Laboratory (GIL) at IIT Bombay, highlight the dynamic energy flow and optimization potential of a V2H-enabled household integrated with solar generation as shown in Figure 12 and Figure 13. During morning and evening peak hours, the EV discharged up to 4 kW to meet residential

demand, substantially reducing dependence on grid power. While parked at the workplace, it charged consistently at 3.5 kW, effectively utilizing surplus solar energy. Over the day, the solar system generated 15.630 kWh, which significantly contributed to local consumption. Notably, the net energy exchange with the grid was -9.277 kWh, indicating that the EV exported more energy than it consumed, demonstrating the potential of V2G systems

⁶² Delta Electronics (Americas), Ltd. V2X Charger 10kW / 208/240Vac: Technical Datasheet. LF_V2X_10kW_V0.1_US. Fremont, CA: Delta Electronics, 2023. [Link](#)

in grid support and peak shaving. Grid energy usage fell from 20.948 kWh (without V2H) to 10.927 kWh (with V2H), confirming the impact of EV-based energy discharge. The EV's energy usage ranged from

0.334 kWh at home to 21.888 kWh at work, with a total discharge of 17.855 kWh, reaffirming its role as a responsive and asset for daily energy balancing and decentralized grid support.

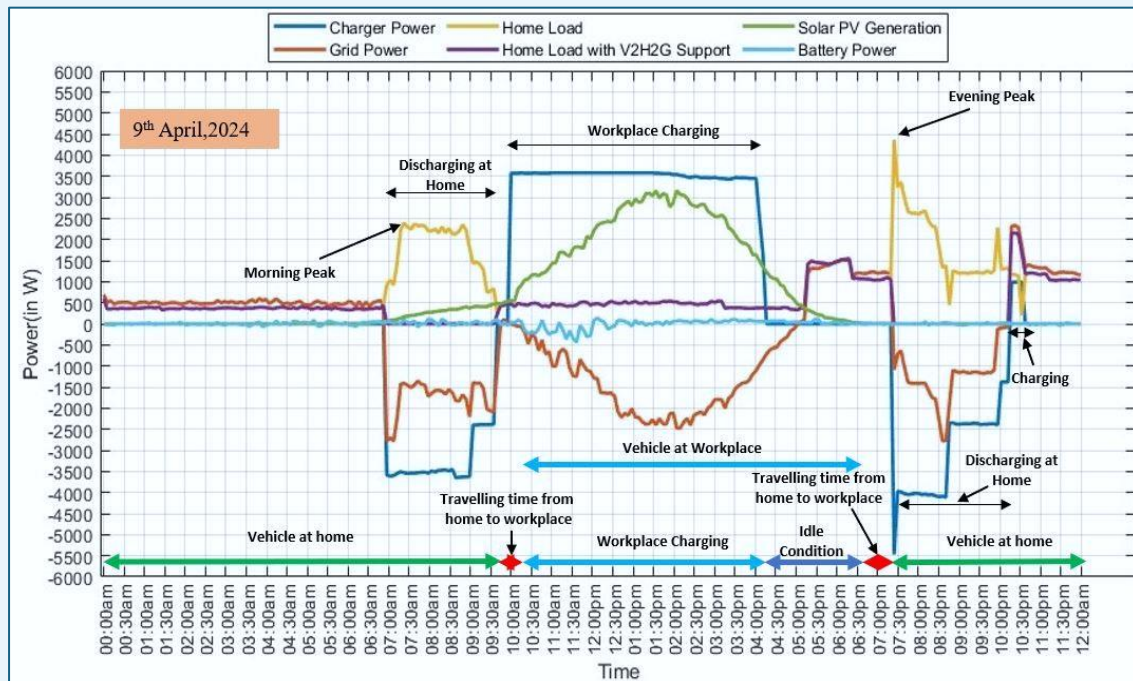


Figure 8: Power Flow Management throughout the day (9th April, 2024)

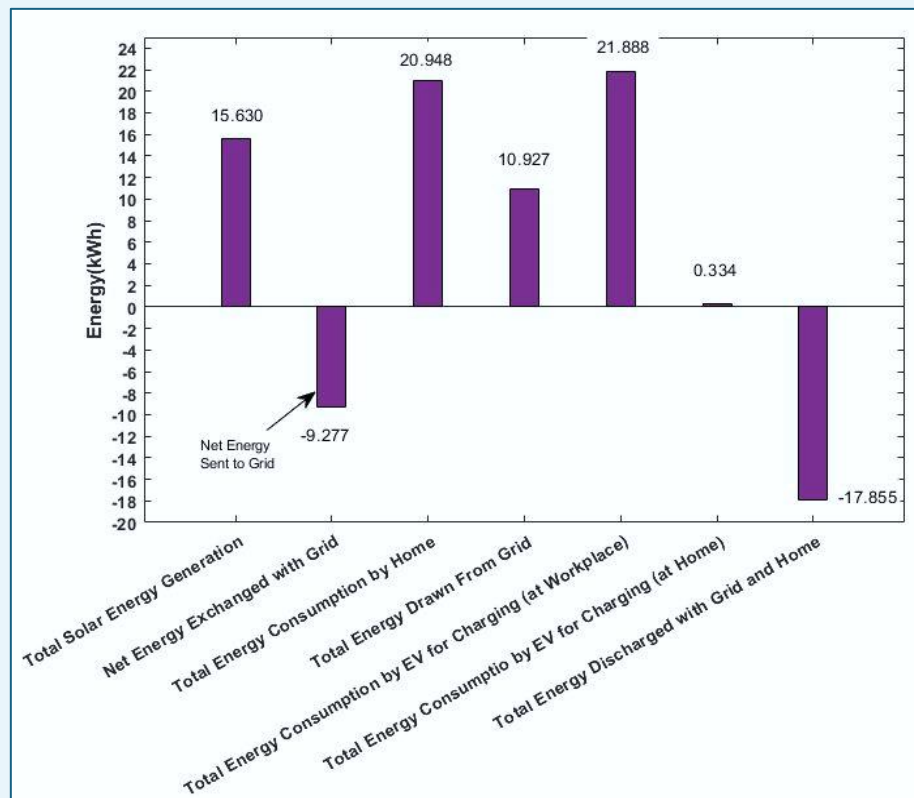


Figure 9: Energy Utilization Throughout the day (9th April, 2024)

7.3 Appendix C: Wiring Diagram of Ford V2H System Integration

The wiring diagram is a fundamental element of any V2H or electric vehicle (EV) charging system, as it provides a clear visual representation of how various electrical components are interconnected and how power flows throughout the system. It plays a vital role in ensuring that the installation is safe, accurate, and compliant with electrical codes and standards. For electricians and system integrators, a well-prepared wiring diagram is essential for understanding the configuration of the charger, main service panel, breakers, grounding mechanisms,

and safety devices. It also serves as a critical reference for system troubleshooting, maintenance, inspections, and future upgrades. In the case of a Ford EV charger setup, the diagram specifically illustrates the structured connections between the main breaker, the Ford Charge Station Pro, and related protective elements to ensure reliable and secure operation.

This section includes four distinct wiring diagrams, each corresponding to a specific system configuration: EV charger, Home Integration System (HIS), solar photovoltaic (PV), and Battery Energy Storage System (BESS). These diagrams align with the system architectures illustrated in Figure 10^{63,64}, and Table 1, providing detailed insight into their electrical integration shown in Chapter 2.

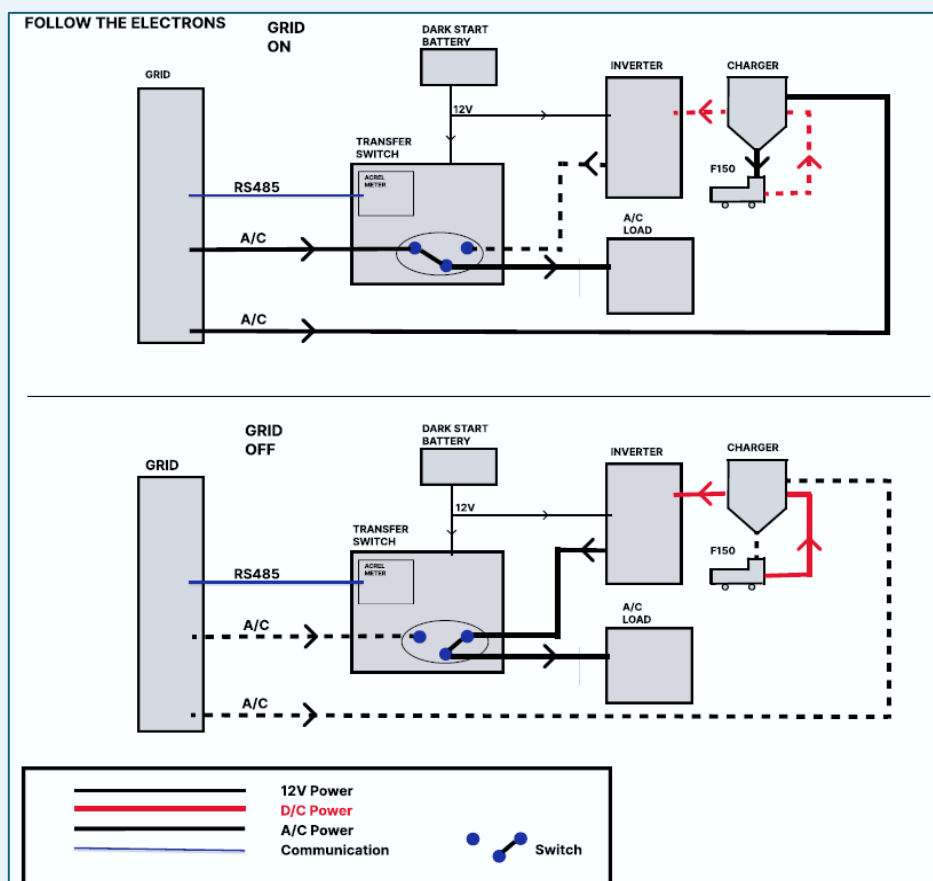


Figure 10: Simplified diagram illustrating power flow within the Ford Home Integration System during grid-connected and grid-disconnected modes, based on Ford's official installation and wiring documentation⁶³

⁶³ Ford Motor Company. Ford F-150 Lightning Owner's Manual Supplement: Vehicle-to-Home (V2H) & Intelligent Backup Power. [Link](#)

⁶⁴ Sunrun. Ford EV Charger Diagrams – Standard Operating Procedures (SOP). [Link](#)

Table 12: Key Components in the Ford Home Integration System Diagram (Error! Reference source not found.)

Key Components in the Ford Home Integration System Diagram

Component	Function/ Role
Transfer Switch	Automatically switches between grid power and vehicle power for home supply.
Actual Meter (CT)	Monitors current flow for energy management and metering purposes.
RS485 Communication	Used for data communication between system components.
Dark Start Battery	Provides 12V power to initiate system startup during grid outages.
Ford F-150 (EV)	Acts as both a power source (Grid OFF) and a load (Grid ON).
EV Charger	Charges the F-150 when grid power is available. Supports bidirectional flow.
A/C Load	Represents the critical household loads powered through the integration system.
Communication Lines	Controls system logic and switching behaviour.
Power Lines (AC/DC)	Denote direction of current for both charging (Grid ON) and discharging (Grid OFF).

7.3.1 EV charger only

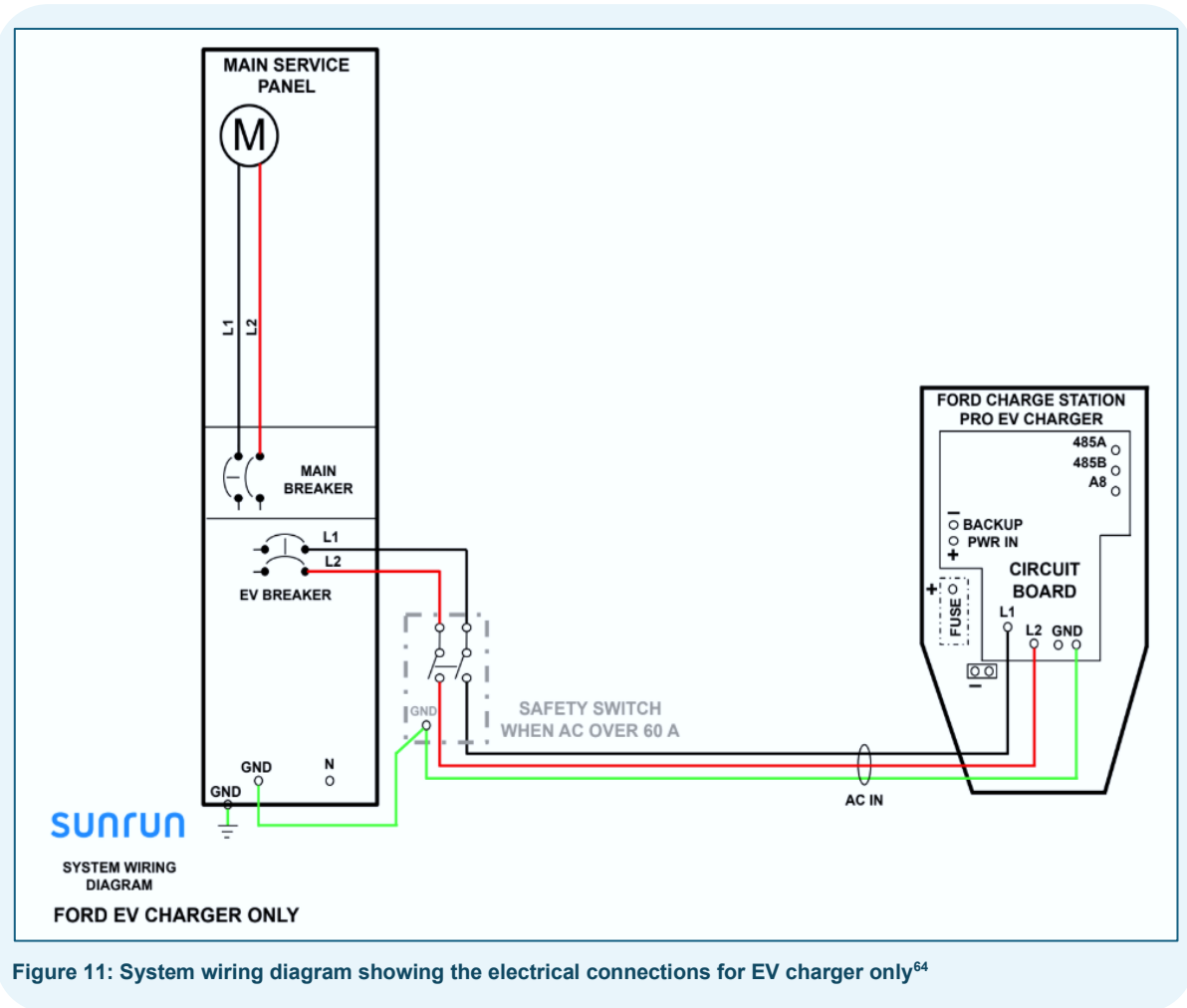


Figure 11: System wiring diagram showing the electrical connections for EV charger only⁶⁴

7.3.2 EV charger with home integration system

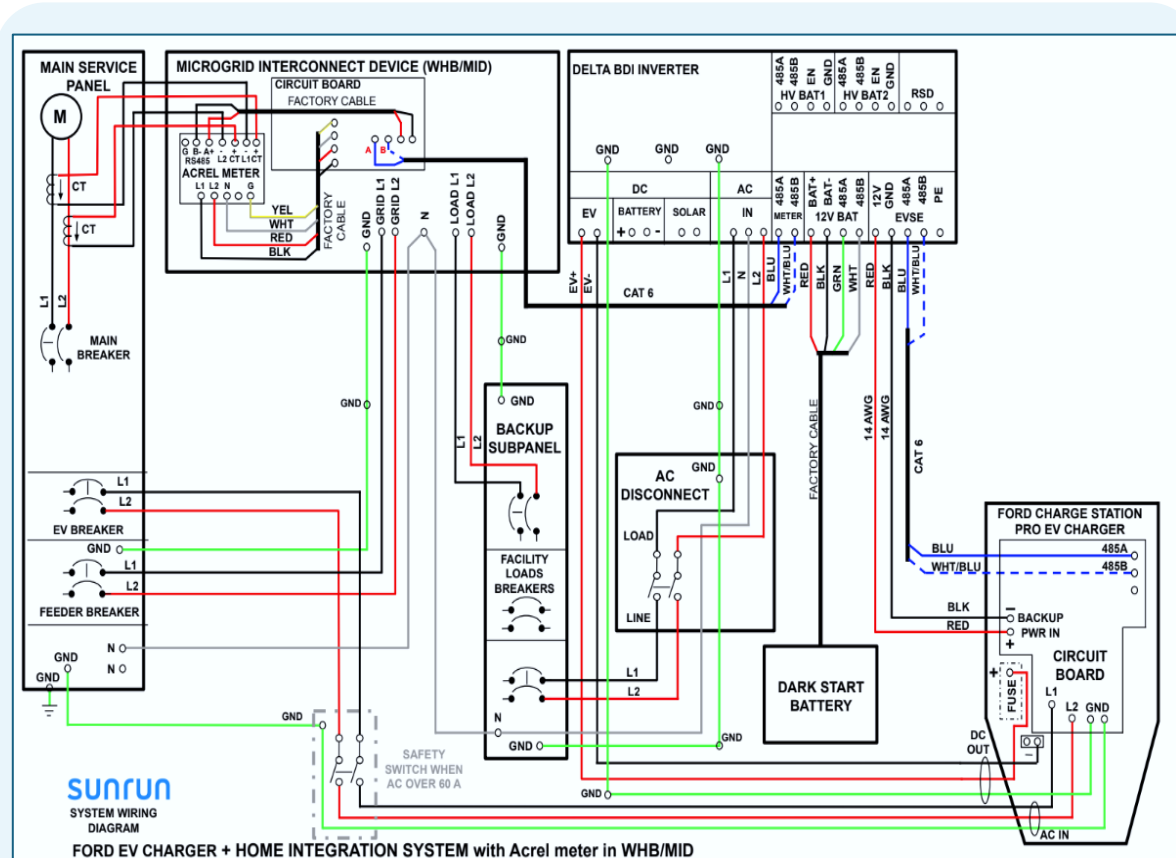


Figure 12: System wiring diagram showing the electrical connections for EV charger and home energy integration system⁶⁴

7.3.3 EV charger with home integration system and solar PV

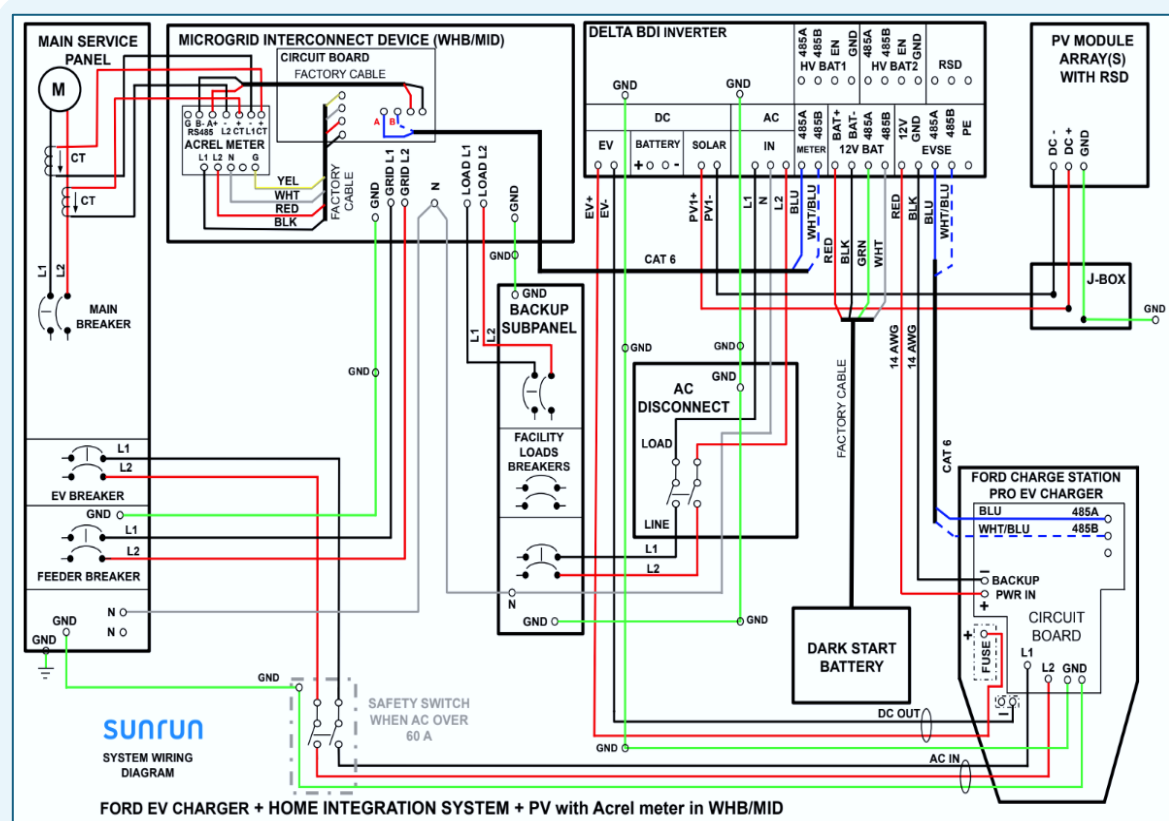


Figure 13: System wiring diagram showing the electrical connections for EV charger, home integration system and solar PV⁶⁴

7.3.4 EV charger with home integration system, solar PV and energy storage system

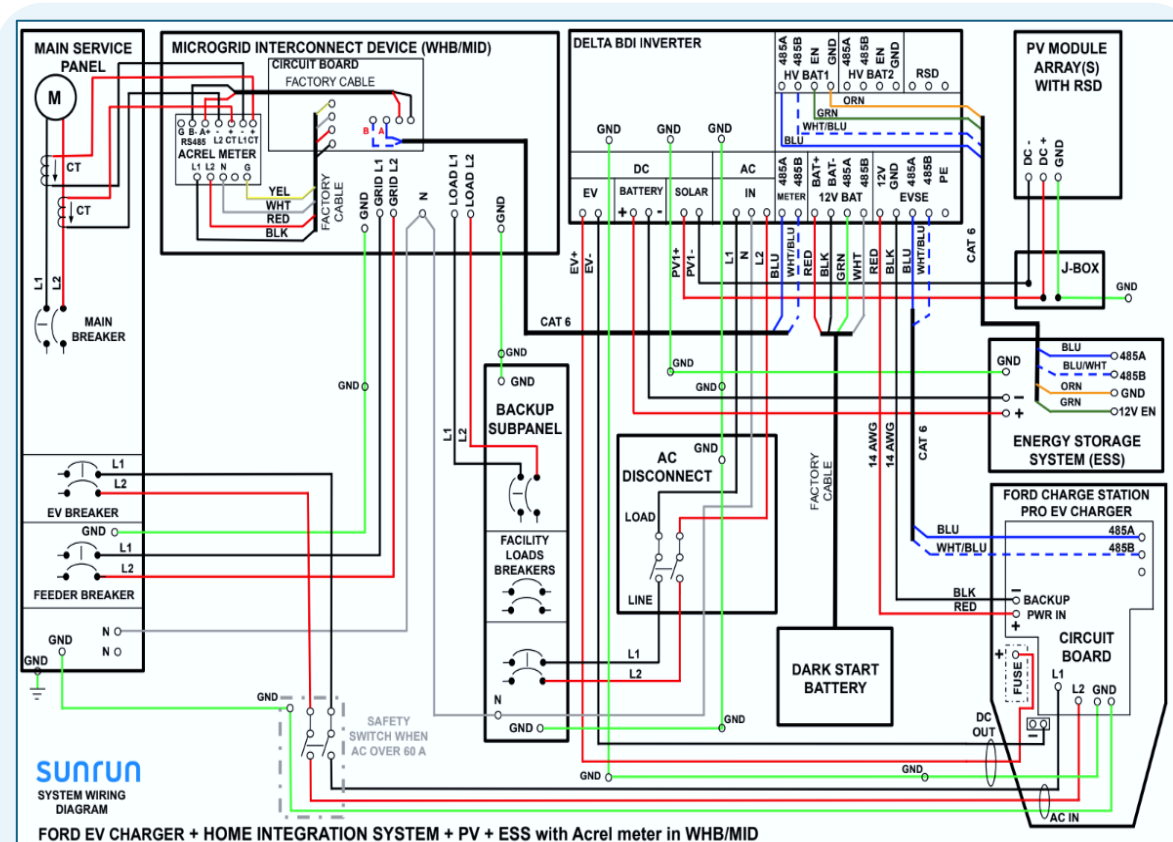


Figure 14: System wiring diagram showing the electrical connections for EV charger, home integration system, solar PV, and energy storage system⁶⁴



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