Vehicle-to-grid (V2G) integration a comprehensive review of technologies, challenges, and opportunities in modern power systems

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Abstract. This comprehensive review explores V2G, where electric vehicles act as mobile energy storage assets for the grid. We systematically analyze the core components of the V2G ecosystem, including bidirectional power electronics, advanced communication protocols such as ISO 15118, and emerging control architectures. The paper evaluates the portfolio of ancillary services that V2G can provide, such as frequency regulation, peak load shaving, and renewable energy firming, while also quantifying the potential adverse impacts on grid stability, including harmonic distortion and voltage fluctuations. Critical barriers to widespread adoption are examined in depth, with a particular focus on the techno-economic implications of battery degradation and the systemic vulnerabilities introduced by cybersecurity threats. Mitigation strategies, including degradation-aware charging algorithms and robust security frameworks leveraging Public Key Infrastructure (PKI) and Transport Layer Security (TLS), are discussed. A techno-economic analysis reveals that V2G profitability is highly contingent on regional electricity market structures and battery chemistry. Our Levelized Cost of Storage (LCOS) analysis indicates that Lithium Iron Phosphate (LFP) chemistry reduces costs by up to 76.3%. Synthesizing findings from international pilots, we highlight deployment status and lessons learned. V2G grid resilience requires overcoming technical, economic, and security challenges.

1 Introduction

The electrification of global transportation transitions EVs from niche products to dominant grid loads, posing stability risks if unmanaged [1, 2]. However, V2G technology reconceptualizes EVs as dispatchable energy storage assets, essential for harmonizing transport and power sectors [3–5]. V2G modernizes the grid by balancing power demand and smoothing renewable intermittency [3, 6–8]. Research has thus matured from foundational battery topics to complex systemic smart grid integration [9–11]. For instance, simulation studies in [9] demonstrate that moderate V2G participation outweighs large-scale smart charging benefits.

This potential is constrained by the "dilemma of dual use": transportation functions rely on battery longevity, conflicting with the cycling required for grid services [1]. V2G must balance revenue against battery degradation [12]. The convergence of low cost LFP chemistry, AI driven degradation control, and cybersecurity vulnerabilities have fundamentally altered V2G viability. We analyze the shift from technical barriers to regulatory frameworks and resilience.

2 V2G ecosystems

V2G requires bidirectional power flow via advanced converters utilizing AC/DC and DC/DC stages. The AC/DC stage acts as a rectifier (G2V) or inverter (V2G), while the DC/DC stage manages current via buck/boost operations [13, 14].

Research in On-Board Chargers (OBCs) focuses on two architectures as illustrated in Figure 1 [13, 14]:

Two-Stage Topologies: Physically separate the AC/DC power factor correction (PFC) from the DC/DC stage. This decoupling simplifies control and optimization but reduces power density.

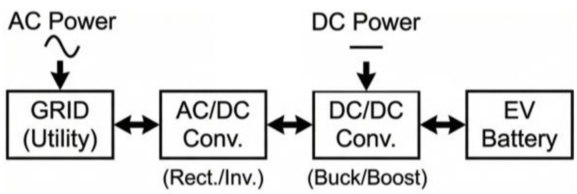

Fig. 1. Bidirectional OBC Topology Enabling V2G/G2V

Single-Stage Topologies: Integrate conversion functions, achieving higher power density and lower costs at the expense of complex control algorithms.

Hardware is evolving toward multifunctionality, defining the OBC as an "energy hub" capable of Vehicle-to-Vehicle (V2V) charging and direct integration with onboard solar [14]. Emerging research

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explores non isolated half bridge converters [15] and bidirectional wireless systems using dual phase shift PWM [16].

2.1 Communication protocols and standards

To manage the bidirectional flow of energy and data safely and interoperably, a robust, standardized communication framework is essential. The V2G ecosystem relies on a "stack" of protocols (Figure 2), each governing a different link in the communication chain.

ISO 15118 anchors this framework. Specifically, ISO 15118-2 (2014) established secure charging via Transport Layer Security (TLS) and Plug & Charge (PnC), allowing automated authentication and billing using digital certificates [17]. This standard underpins the Combined Charging System (CCS) [18].

The 2nd-gen ISO 15118-20 (2022) unlocks full V2G by standardizing Bidirectional Power Transfer (BPT) and IP-based communication [19].

However, ISO 15118 (governing the EV-to-EVSE link) is only one piece of a larger, more complex protocol stack:

OCPP (Open Charge Point Protocol): This standard backend protocol links EVSE to CSMS. Version 2.0.1 integrates ISO 15118 for smart charging and V2G reporting [19, 20].

IEEE 2030.5 (Smart Energy Profile 2.0): This application-layer protocol manages Distributed Energy Resources (DERs). It bridges V2G aggregators and utility operators (e.g., DERMS) [21], as demonstrated in the Maui V2G pilot project [22].

IEC 61850: A foundational utility automation standard, it models V2G assets as DERs within grid operations [19].

The interplay between these standards creates a complex attack surface; vulnerabilities in one layer can facilitate pivot attacks across the system [23].

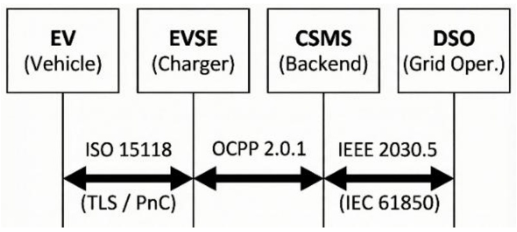

Fig. 2. The V2G communication protocol stack, illustrating the standards used at interfaces between the Electric Vehicle (EV), Supply Equipment (EVSE), Management System (CSMS), and Grid Operators.

2.2 Centralized vs. distributed control

Coordinating millions of EVs is a monumental challenge [1, 24]. Centralized Control relies on a single aggregator directly managing the charging profiles of all connected EVs, which offers theoretical optimality but suffers from computational bottlenecks, scalability limits, and privacy issues [24–26]. Distributed Control moves intelligence to the edge (EV/EVSE), allowing local controllers to optimize their energy dispatch using algorithms like the Alternating Direction Method of Multipliers (ADMM), thereby reducing communication overhead [27].

3 Grid services and impacts

V2G integration introduces duality: EVs act as stability resources or disruptive loads, determined entirely by control strategies.

3.1 Portfolio of ancillary services

When intelligently controlled, aggregated EV fleets can provide a wide portfolio of ancillary services, which are essential functions for maintaining the stability, reliability, and quality of the power grid [28, 29].

Frequency Regulation [29]: V2G fleets act as distributed BESS, injecting/absorbing power during under/over frequency events via droop control..

Peak Load Shaving [29]: EVs charge during off peak "valleys" and discharge during peak demand, flattening load curves and deferring infrastructure upgrades [12, 28].

Renewable Energy Firming: V2G mitigates intermittency by time shifting surplus solar/wind generation to demand peaks) [30].

Other Services: Beyond these three, V2G fleets are technically capable of providing spinning reserves (capacity that can be deployed within minutes) [1], voltage support (injecting/absorbing reactive power) [28], and even black start capability to help restart parts of the grid after a major outage [29].

A hierarchy exists between V1G (smart unidirectional charging) and V2G. While V1G minimizes degradation, true V2G unlocks high value markets (spinning reserves, voltage support) at the cost of increased cycling [28].

3.2 Grid stability and power quality

Conversely, uncontrolled V2G deployment can inject disturbances into the grid via nonlinear inverters [12, 31]. Harmonic Distortion, particularly at specific orders (11th, 13th) and emerging supraharmonics (2-150 kHz), degrades power quality and equipment [1, 32]. Voltage Fluctuations occur when simultaneous charging creates bulk loads, causing sags [4, 5, 33]. A recursive challenge involves chargers altering local grid impedance, potentially aligning resonance frequencies with harmonic emissions to create instability [32].

4 Barriers and mitigation

Widespread adoption is hindered by the techno-economic cost of battery degradation and systemic cybersecurity risks.

4.1 Degradation and costs

The "excessive strain on EV batteries" is consistently identified as the single most critical barrier to V2G deployment. This degradation is the primary cost that must be offset by V2G revenue, making it the "decisive factor" in the techno-economic equation [12]. Battery degradation is driven by two primary mechanisms:

Cyclic Aging: This refers to stress (e.g., lithium plating, cracking) primarily influenced by Depth of Discharge (DoD), C-rates, and temperature [34].

Calendar Aging: This passive degradation occurs when idle. High temperatures and State of Charge (SoC) [35] accelerate it by driving electrolyte oxidation and SEI growth.

While studies show 9-14% wear, the "degradation paradox" challenges the view that V2G always harms. [34, 36]. A 2022 study compared unmanaged high SoC idling (90-100%) against smart V2G cycling (90-65%). Counter intuitively, V2G reduced degradation by 0.95% [37]. Reduced high SoC calendar aging (via lower average SoC) outweighed V2G cyclic aging, primarily by minimizing loss of lithium inventory (LLI) [36, 37]. This implies that a "smart" V2G algorithm can, in some cases, extend a battery's life compared to the common charging behavior of leaving a vehicle at 100% SoC.

4.2 Mitigation via degradation-aware

Software solutions utilize AI, such as Proximal Policy Optimization (PPO) and Long Short-Term Memory (LSTM) networks, to co-optimize revenue and health. Models lacking aging awareness underestimate costs by approximately 30% [38, 39]. These principles are also applicable to second-life battery management [40].

4.3 Cybersecurity threats

V2G expands the grid's attack surface to millions of mobile endpoints. A systematic review (2020–2024) identifies critical threats [41].

1) Identified Threats: These include data-centric attacks like Man-in-the-Middle (MITM) [42], data manipulation, and privacy violations, as well as availability attacks like Denial-of-Service (DoS). Physical layer attacks have also been demonstrated, such as the "Broken wire" attack, which uses targeted radio frequency (RF) signals to terminate CCS charging sessions remotely [41].

2) Identified Vulnerabilities: The most alarming vulnerabilities are not theoretical but practical, stemming from poor implementation and legacy systems.

a) Protocol Implementation Failure: A 2024 measurement study of 325 publicly deployed CCS charging stations found that an alarming 88% did not implement TLS encryption at all, leaving them vulnerable to basic eavesdropping and manipulation attacks that have been known for years [17].

b) Legacy Protocols: Field testing of V2G sites revealed the pervasive use of insecure, unencrypted legacy protocols like Telnet and Modbus/TCP. This allowed testers to easily capture administrator passwords and, more critically, "recover and reissue. Modbus commands" to gain "complete control over the V2G implementation" and its energy flow [43].

c) Physical security: A lack of physical locks on equipment cabinets allows attacker to gain direct network access, bypassing all digital defenses [43].

The most profound finding of the 2024/2025 systematic review, however, is not what is being researched, but what is being ignored. The analysis of 133 papers revealed two critical research gaps [41]:

1) Protection vs. Recovery: 103 studies (77%) focused on protection (preventing an attack), while only 7 studies (<6%) addressed recovery (how to operate and restore the system after a successful attack) [41].

2) Human Factor: None of the 133 studies focused on "the linkage between the behavior of EV users and the cybersecurity of V2G systems" [41].

This exposes a massive blind spot in current V2G research. The community is focused on building technological "walls" (e.g., AI, blockchain) while neglecting both operational resilience (recovery) and the most common attack vector: the human user.

4.4 Mitigation via robust security frameworks

Defense-in-depth is required. Foundational PKI and TLS implementation is nonnegotiable for encryption and trust (PnC) [17, 43]. While TLS (ISO 15118-2) encrypts traffic to prevent attacks, PKI establishes the "trust framework." Using digital certificates for mutual authentication, PKI validates EV and EVSE legitimacy, enabling secure Plug & Charge transactions [43]. As the threat landscape evolves, defenses must integrate advanced technologies. Blockchain is proposed to enhance decentralized trust by creating immutable, transparent ledgers for all energy and financial transactions, making data tampering computationally infeasible [41]. Furthermore, Artificial Intelligence (AI) algorithms are being deployed for real-time anomaly detection, capable of identifying dynamic malicious behaviors that static firewalls miss [41]. Federated Learning (FL) enables collaborative training of threat detection models without sharing sensitive data [27].

5 Techno-economic analysis

Revenue is driven by energy arbitrage and ancillary services. In volatile markets (e.g., Germany), net revenues can reach €23,000 over a vehicle's life [35, 44]. Conversely, in markets with flat tariffs or price differentials below the calculated break-even point of approximately 0.11 EUR/kWh, the revenue generated is insufficient to cover the cost of accelerated battery wear, rendering V2G unprofitable [35, 44].

Since degradation is the single largest operational cost, the choice of battery chemistry is paramount. While NCM (Ternary) batteries offer high energy density, they rely on expensive, geopolitically sensitive materials (cobalt, nickel) and suffer from lower thermal stability and shorter cycle life [45–47]. In contrast, LFP chemistry has emerged as the superior choice for V2G applications. LFP offers a dramatically longer lifespan (with some manufacturers guaranteeing up to 10,000 cycles), significantly lower production costs, and enhanced safety features [46–48]. Recent techno-economic assessments confirm that transitioning to LFP batteries can reduce the Levelized Cost of Storage (LCOS) by up to 76.3% compared to NCM, solidifying LFP as the primary enabler for economic viability [49].

Validating these findings, a review of major international pilot projects moves the analysis from theory to practice, highlighting real-world successes and persistent barriers.

a) *Case Study 1*: Smart Solar Charging (Utrecht) links bidirectional AC chargers, PV, and car sharing. Using 50 cars (200 kW) for congestion management, it identified "battery anxiety" and degradation concerns as B2C barriers requiring compensation [50, 51].

b) Case Study 2: The "Parker" Project (Denmark) validated V2G across brands like Nissan and Peugeot. Using 10 kW DC CHAdeMO chargers, it proved reliable delivery of Frequency Containment Reserves (FCR) [54]. The project set a benchmark of €1,860 per car/year from grid services [52].

c) Case Study 3: London's 'Bus2Grid' aggregated 28 buses into a 1.1 MW "virtual power station". It proved fleets with predictable schedules are an ideal V2G entry market, avoiding B2C anxiety [53, 54].

The synthesis of these and other key European pilot projects reveals a clear set of "lessons learned" regarding the practical barriers to deployment:

Pilots prove V2G feasibility and integration with EU renewable goals. While private users need compensation for "battery anxiety", fleets offer the strongest initial business case. Critical Barriers:

d) Economic: High upfront costs of bidirectional chargers hinder residential users, with a premium of thousands

e) Technical: Interoperability is hindered by the "standards chasm" between proven CHAdeMO and mandated CCS, plus fragmented ISO 15118 implementation.

f) Regulatory: "Regulatory lag" creates bottlenecks via slow permitting, punitive taxation, and unclear aggregator frameworks, a gap TSOs like ENTSO-E are now addressing.

6 Conclusion

This review finds V2G viability reshaped by LFP adoption, AI degradation control, and cybersecurity gaps. The primary challenge shifts from technical feasibility to establishing regulatory and security frameworks for commercial scale.

Our synthesis points not to broad "gaps" but to three critical paths that are imperative for V2G commercialization:

1) *Develop Value-Stacking Frameworks*: Research must validate models enabling V2G assets to serve multiple markets simultaneously (e.g., frequency regulation). This requires regulatory updates and stakeholder engagement, aligning with European Green Deal renewable integration goals [12].

2) *Build for Resilience*: Protection alone is insufficient; research must prioritize recovery protocols for inevitable attacks. Additionally, the "human factor" must be treated as a critical attack vector, not just an optimization variable [41].

3) *Mandate Pan-European Protocols*: Interoperability remains a barrier. Research must prescribe full-stack harmonization (ISO 15118, OCPP, IEEE 2030.5). Collaboration with ENTSO-E is vital to develop standards and grid codes for seamless, cross-border V2G.

Achieving a green grid requires integrating EV power management with robust data security. Success depends on blending power engineering, data science, and policy into a unified strategy.

Success depends on blending power engineering, data science, and policy into a unified strategy. Future work should focus on large-scale field validation of these unified frameworks, particularly evaluating the real-world performance of federated learning in decentralized V2G networks and standardizing post-cyberattack recovery protocols.

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