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Embedded Systems in Vehicle-to-Grid (V2G) Applications: Progress and Challenges

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Abstract. The global push toward carbon neutrality and the rapid adoption of electric vehicles (EVs) have created new opportunities and challenges for modern power systems. Vehicle-to-Grid (V2G) technology enables bidirectional power exchange between EVs and the grid, transforming vehicles into distributed energy storage units that can support peak shaving, renewable energy integration, and ancillary services. Embedded systems are at the core of Vehicle-to-Grid implementation, providing real-time monitoring, control of power electronic converters, battery management, and secure communication. This paper reviews recent progress in embedded systems applied to V2G, with particular focus on their role in battery management systems (BMS), embedded control strategies for bidirectional converters, and communication protocols. Applications in renewable energy integration, microgrids, and residential energy management are discussed. This paper highlights critical challenges including battery degradation, scalability of real-time scheduling, interoperability, and cybersecurity. Future development trends such as edge artificial intelligence, digital twins, and blockchain-based energy trading are also explored. By synthesizing current literature, the paper underscores the central role of embedded systems in enabling V2G and shaping the next generation of smart and sustainable power systems.

Keywords: Vehicle-to-Grid (V2G), Embedded Systems, Renewable Energy, Battery Management

1. Introduction

The ongoing global energy transition is driven by the dual imperatives of reducing carbon emissions and increasing reliance on renewable energy. Renewable sources such as wind and solar are expanding rapidly; however, their variability and intermittency create operational challenges, including frequency instability, voltage fluctuations, and the curtailment of excess generation. In parallel, the rapid adoption of electric vehicles (EVs) is transforming both the transportation and energy sectors. BloombergNEF projects that EVs will account for nearly one-third of global new car sales by 2030, a figure that represents a significant share of both electricity demand and distributed storage capacity [1].

Vehicle-to-Grid (V2G) technology addresses both opportunities and challenges by enabling bidirectional power flow between EVs and the grid. Through V2G, EVs can provide services such as

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peak shaving, load balancing, and renewable energy integration, enhancing the flexibility and resilience of power systems [2,3]. Several pilot projects in Japan, Denmark, and the United Kingdom have demonstrated the technical feasibility of V2G; however, challenges still remain in achieving large-scale deployment.

At the heart of V2G are embedded systems, which provide the computational and control backbone for energy exchange. Embedded controllers enable accurate state estimation in battery management systems (BMS), implement advanced control strategies for bidirectional converters, and ensure interoperability through standardized communication protocols. Furthermore, integration with Internet of Things (IoT) platforms and edge computing extends the intelligence of embedded systems to fleet-level coordination and predictive maintenance [4,5].

This paper aims to review the current state of embedded systems in V2G applications, highlighting their roles, challenges, and future trends. It focuses on three main aspects: the ways in which embedded systems enable the safe and efficient operation of V2G, the technical barriers constraining large-scale deployment, and the emerging technologies with the potential to further enhance system performance. By addressing these aspects, the paper contributes insights into the design of next-generation embedded systems for sustainable energy integration.

2. Vehicle-to-Grid (V2G) technology overview

2.1. Definition and architecture of V2G

Vehicle-to-Grid (V2G) refers to the bidirectional flow of both electricity and information between electric vehicles (EVs) and the power grid. Unlike traditional unidirectional charging, V2G enables EVs to discharge stored energy back into the grid when required, acting as mobile distributed storage units [2]. The core architecture typically includes:

·Electric Vehicles (EVs): Equipped with high-capacity lithium-ion batteries.

·Bidirectional Chargers based on power electronics: Responsible for converting AC–DC and DC–AC in both charging and discharging modes.

·Embedded Controllers: Manage real-time energy flow, ensure compliance with grid codes, and maintain safety.

·Communication Modules: Enable interoperability through standards such as ISO 15118 and OCPP.

·Distribution Grid (part of modern smart grids): The end-user system receiving and supplying electricity.

Figure 1 illustrates the overall V2G system, showing the interaction between EVs, embedded controllers, chargers, communication modules, and the distribution grid.

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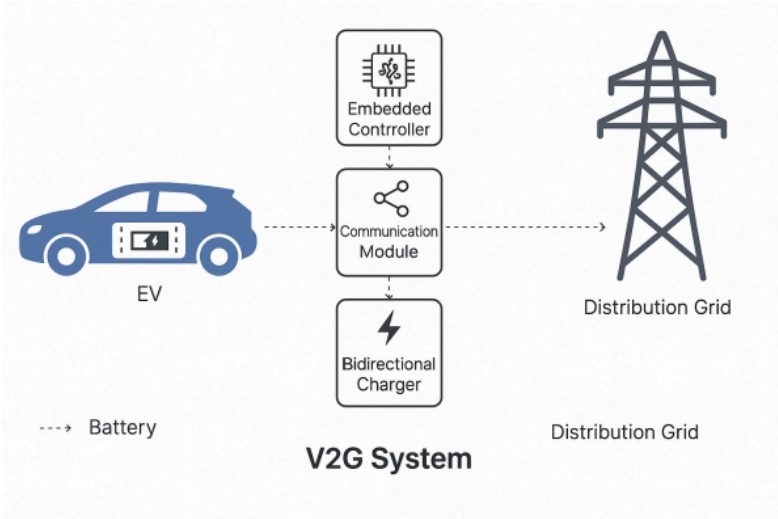

Figure 1. V2G system architecture

2.2. Applications: peak shaving, virtual power plants, and emergency power supply

The flexibility of V2G supports a range of applications.

First, EVs can discharge stored power during high-demand periods, thereby achieving peak shaving and load balancing while reducing operational stress on critical grid infrastructure. In addition, aggregated EV fleets coordinated by embedded systems can function as virtual power plants (VPPs), acting as dispatchable resources that enhance grid stability [3]. Moreover, in residential settings, EVs can supply households with electricity during outages, which provides an emergency power supply (V2H) and enhances resilience.

Table 1 summarizes representative V2G pilot projects worldwide. These case studies demonstrate technical feasibility and highlight diverse application contexts.

Table 1. Selected V2G pilot projects

Country	Project Name	Scale (EVs)	Key Features	Reference
Japan	Nissan Leaf V2G	10,000+	Vehicle-to-Home, disaster resilience	[2]
Denmark	Nuvve V2G Trial	400+	Frequency regulation, fleet integration	[3]
U.K.	OVO Energy V2G	1,000+	Residential charging + grid balancing	[4]

3. Role of embedded systems in V2G

Embedded systems are the backbone of Vehicle-to-Grid (V2G) technology, enabling real-time monitoring, control, and secure communication between electric vehicles and the grid. Their role spans three major domains: battery management, power electronic interfaces, and communication networking. Together, these subsystems ensure that V2G operations are safe, efficient, and interoperable.

3.1. Embedded systems in Battery Management Systems (BMS)

The battery management system (BMS) is one of the most critical components in EVs, responsible for monitoring and controlling battery operation. Without robust embedded control, V2G

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participation would risk accelerated degradation or even failure of batteries.

Key tasks of embedded BMS include:

State of Charge (SOC) Estimation: SOC provides the available capacity of a battery. Common approaches are coulomb counting, extended Kalman filtering, and increasingly, machine learning algorithms that exploit voltage and current patterns [5].

·State of Health (SOH) Monitoring: SOH evaluates the long-term degradation of batteries. Embedded systems track internal resistance, capacity fade, and thermal stress, enabling predictive maintenance.

·Thermal Management: Embedded controllers regulate active or passive cooling systems to prevent overheating during intensive V2G charge-discharge cycles.

·Hardware Platforms:

MCUs (e.g., ARM Cortex-M) → cost-efficient, suitable for simpler EVs.

DSPs (e.g., TI C2000 series) → optimized for real-time control and SOC/SOH estimation.

FPGAs → allow parallel processing and reconfigurability, suitable for advanced algorithms.

Table 2. Comparison of SOC estimation methods in embedded BMS

Method	Accuracy	Computational Cost	Real-time Suitability	Notes
Coulomb Counting	Low–Medium	Very Low	High	Sensitive to drift over time
Extended Kalman	High	Medium	Medium	Widely used in EV BMS
Neural Networks	High	High	Medium–Low	Requires training & dataset

Table 2 compares common SOC estimation methods implemented in embedded BMS, systematically highlighting their key trade-offs in terms of estimation accuracy, computational cost, and suitability for real-time operation. Coulomb counting is computationally efficient and suitable for simple applications, but its accuracy degrades over time due to drift. Extended Kalman filtering provides higher accuracy and has been widely adopted in EV BMS, though it requires moderate computational resources. Neural network–based approaches achieve high accuracy and adaptability but are constrained by high computational costs and the need for extensive training data. This comparison emphasizes that the selection of SOC estimation algorithms in embedded systems must balance accuracy with hardware limitations and real-time constraints.

3.2. Embedded control of power electronic interfaces

The bidirectional flow of energy between EVs and the grid relies on efficient power electronic interfaces, including DC/DC converters and DC/AC inverters,which are fundamental enablers of V2G services in smart grids. Embedded systems govern these converters by implementing advanced control strategies, ensuring compliance with grid codes, and optimizing efficiency as shown in table 3.

Control Strategies:

Proportional-Integral(PI)Control: Simple, widely implemented, but limited in handling nonlinearities.

Model Predictive Control (MPC): Offers superior dynamic performance, predictive capability, and multi-variable handling, but requires more computational power [6].

Field-Oriented Control (FOC): Common in EV traction and grid-interfaced inverters, balancing speed and accuracy.

Wide-Bandgap Devices:

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Embedded systems also control converters using silicon carbide (SiC) and gallium nitride (GaN) devices. These allow higher switching frequencies and lower losses compared to traditional silicon, improving efficiency of V2G operation [7].

Table 3. Embedded Hardware Platforms for Power Converter Control

Hardware Platform	Processing Speed	Cost	Flexibility	Application Context
MCU	Moderate	Low	Low	Basic charging/discharging
DSP	High	Medium	Medium	Real-time current/voltage control
FPGA	Very High	High	High	Advanced MPC, reconfigurable logics

This comparison shows that MCUs are cost-effective but limited, while FPGAs support cutting-edge control strategies at higher costs.

3.3. Embedded communication and networking

Effective communication ensures coordination between EVs, chargers, aggregators, and grid operators. Embedded systems implement and secure communication channels.

Standards and Protocols:

ISO 15118: Defines Plug-and-Charge authentication and energy communication between EVs and chargers.

OCPP(Open Charge Point Protocol): Provides interoperability for charging stations across different vendors.

IoT and Edge Computing:

Embedded devices integrate IoT modules (e.g., LoRa, NB-IoT, 5G) to support scalable V2G deployment. Edge computing enables local decision-making, reducing latency and dependence on cloud servers [8].

Cybersecurity:

As V2G is a cyber-physical system, embedded modules must ensure authentication, encryption, and intrusion detection. Hardware Security Modules (HSMs) embedded into controllers can prevent malicious access.

4. Applications in renewable energy integration

The integration of renewable energy sources such as solar and wind is central to achieving carbon neutrality, but their intermittency challenges the stability and reliability of modern power systems. Vehicle-to-Grid (V2G) technology, empowered by embedded systems, provides a promising solution by utilizing electric vehicles (EVs) as flexible and distributed storage units. Recent studies confirm that V2G not only enhances renewable penetration but also mitigates curtailment and improves overall grid resilience [9][10].

4.1. Smart microgrids and distributed energy management

Smart microgrids combine renewable generation, storage, and controllable loads, coordinated through embedded systems and power electronics, to achieve local autonomy and seamless interaction with smart grids. Embedded systems within EVs facilitate real-time coordination of charging and discharging according to renewable availability and demand forecasts. For instance, during periods of high photovoltaic output, embedded controllers schedule EV charging, while

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during low generation, they dispatch energy back to support local loads. Advanced scheduling algorithms implemented on embedded hardware allow microgrids to maintain voltage stability, reduce curtailment, and increase renewable penetration [11].

4.2. Virtual Power Plants (VPP) aggregating EVs

By aggregating thousands of EVs, VPPs create a flexible, large-scale energy resource for the grid as shown in table 4. Embedded systems play a critical role in enabling this aggregation by ensuring reliable two-way communication, fleet-level coordination, and decentralized energy optimization. For example, the Danish Nuvve project demonstrated that EV fleets controlled by embedded systems can provide frequency regulation services comparable to traditional generators [3]. VPPs leverage embedded edge computing devices to reduce latency and balance local decision-making with global optimization.

Table 4. Benefits of EV Aggregation in VPPs

Benefit	Embedded Role	Impact on Grid
Frequency Regulation	Real-time converter control	Improved grid stability
Peak Shaving	Fleet-level scheduling	Reduced peak demand
Renewable Integration	Predictive charging/discharging	Increased utilization of renewables

4.3. Vehicle-to-Home (V2H) and residential energy management

In residential contexts, V2H leverages EVs as mobile backup power sources and tools for household energy optimization. Embedded systems integrate with home energy management platforms to schedule charging during off-peak or high-renewable periods, and schedule EV discharging during demand peaks to lower household electricity costs. Wiley pointed out that advances in bidirectional converter technologies and edge intelligence allow seamless switching between grid-connected and islanded modes, ensuring reliability and safety [12]. Moreover, Rao emphasized that the wide adoption of V2H not only benefits individual users but also enhances the flexibility of residential distribution networks, especially under increasing renewable energy variability [13].

5. Challenges and research gaps

Despite significant progress, several technical and practical challenges still hinder the large-scale adoption of Vehicle-to-Grid (V2G). Embedded systems, while central to V2G, face limitations that must be addressed to ensure reliable and sustainable operation. These challenges can be broadly categorized into issues related to battery degradation, real-time scheduling and optimization, system reliability and cybersecurity, standardization and interoperability, as well as economic and policy barriers. The following subsections discuss each of these aspects in detail.

5.1. Battery degradation and lifetime optimization

Frequent charge/discharge for ancillary services accelerates aging via mechanisms such as SEI growth, lithium plating at low temperatures/high C-rates, and increased internal resistance. Empirical evidence indicates that indiscriminate V2G cycling can shorten lifetime and thus erode owner value [14]. From an embedded-systems perspective, three gaps are prominent:

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1. Health-aware state estimation: SOC alone is insufficient; high-fidelity SOH and RUL (Remaining Useful Life) estimation must run online on resource-constrained embedded controllers. Kalman-filter variants and data-driven estimators reviewed in [5] need on-board adaptation (e.g., incremental parameter identification) to remain robust under varying DOD, temperature, and C-rates.

2. Multi-objective scheduling: Health-aware MPC that limits throughput energy and penalizes deep cycles can reduce wear while meeting grid services [5][6]. Real-time realizations must trade optimality for bounded latency on MCUs/DSPs, and enforce safety constraints (voltage, temperature) at the control loop level.

3. Cost internalization: The battery wear cost models in [14] should be embedded into local decision policies and aggregator settlements so that owners are compensated for marginal degradation, turning longevity into a first-class control objective.

5.2. Real-time scheduling and optimization algorithms

Coordinating thousands of EVs across heterogeneous networks is a classic large-scale optimization problem with strict timing. Centralized dispatch suffers from solver and communication bottlenecks; fully distributed approaches risk inconsistency under delays and packet loss, particularly when coordinating thousands of power electronic converters within smart grid infrastructures[6]. A research priority is hierarchical, time-scale-separated control: converter-level loops (ms) on the charger, local energy managers (s–min) at the edge, and fleet optimization (min–hr) at the aggregator. Lightweight ADMM-style or receding-horizon schemes suitable for MCUs/DSPs can bound computation while preserving convergence guarantees [5]. Embedded design must include deadline analysis, admission control under bandwidth limits, and fallbacks to safe islanded modes when connectivity degrades.

5.3. Reliability and security of embedded systems

V2G is a cyber-physical system; failures propagate from code to converters to the grid. On the reliability side, wide-bandgap switching (SiC/GaN) increases dv/dt and EMI, which stresses sensors and control electronics; thermal cycling and component aging jeopardize the MTBF of chargers. Controllers require redundancy (lockstep cores, watchdogs), run-time diagnostics, and safe-state strategies. On the cybersecurity side, threats include spoofing of EV identities, manipulation of price/dispatch signals, and denial-of-service on charge points. Embedded countermeasures should implement secure boot, hardware security modules for key storage, certificate-based mutual authentication (aligned with ISO-15118 Plug-and-Charge), integrity-checked OTA updates, and anomaly detection at the edge [8][15]. A gap remains in proving these protections under tight memory/CPU budgets and variable connectivity.

5.4. Standardization and interoperability issues

Fragmented interfaces hinder portability across OEMs and regions. While ISO 15118 and OCPP have improved interoperability, optional feature sets and version skew complicate conformance; grid-code differences further burden firmware variants [3][8][15]. Needed research includes: (i) formal interface models that allow machine-checkable conformance; (ii) protocol translation at the edge without semantic loss; and (iii) testbeds for cross-vendor validation with fault injection covering timing, packet loss, and degraded power quality.

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5.5. Economic and policy barriers

The economics of V2G depend on local tariffs, battery wear, and distribution constraints. Distribution networks may face transformer over-loading and voltage excursions if unmanaged charging/discharging aligns unfavorably with load [16]. Conversely, coordinated V2G improves renewable utilization and reduces system costs/emissions [9][17]. Embedded systems should therefore support settlement transparency (e.g., logging verifiable energy data and service quality metrics), owner-centric policies (e.g., opt-in, minimum SOC constraints), and market-signal ingestion at the edge. A research gap remains in aligning health-aware control with market products so that compensation consistently exceeds expected degradation costs [14], while respecting feeder limits identified in distribution studies [16].

Figure 2 illustrates the core findings of Section 5: V2G deployment is mainly constrained by battery degradation, real-time scheduling challenges, cybersecurity risks, standardization issues, and immature business models. Among these, battery health issues and interoperability challenges stand out as the most severe, highlighting the need for embedded intelligence that balances technical performance with long-term sustainability.

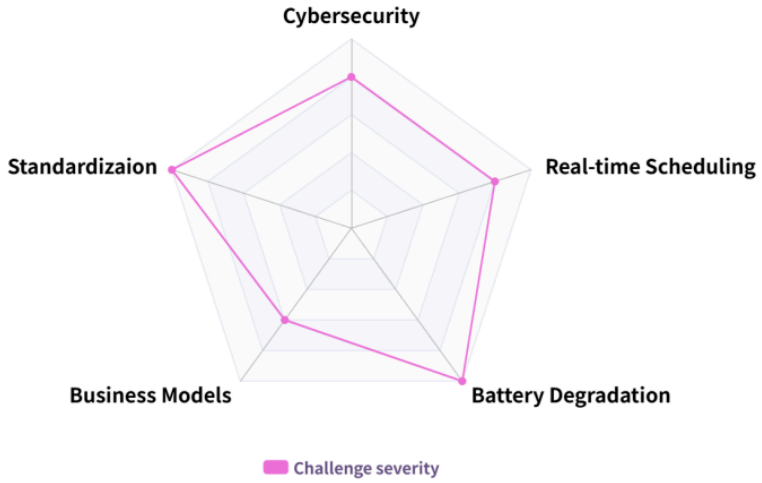

Figure 2. Radar chart of V2G challenges

6. Conclusion

This paper has reviewed the role of embedded systems in enabling Vehicle-to-Grid (V2G) applications, emphasizing their importance in battery management, power electronics, and communication. By providing real-time control, accurate state estimation, and secure data exchange, embedded systems are indispensable to the safe and efficient operation of V2G. Applications such as smart microgrids, virtual power plants, and vehicle-to-home systems demonstrate the potential of EVs to act as distributed energy storage resources, supporting renewable energy integration and enhancing grid flexibility.

Nevertheless, several research gaps remain. Battery degradation continues to limit user acceptance, while real-time scheduling and fleet coordination pose scalability challenges. The reliability and cybersecurity of embedded controllers are critical concerns in a cyber-physical context, and interoperability remains constrained by fragmented standards. In addition, uncertainties in economic incentive mechanisms and market frameworks hinder the widespread participation of EV owners.

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Looking ahead, future research should focus on integrating edge artificial intelligence, lightweight machine learning (TinyML), and digital twins into embedded platforms, enabling predictive maintenance and distributed optimization. Emerging technologies such as blockchain for secure energy trading and high-performance hardware based on SiC, GaN, and RISC-V processors can further enhance efficiency and reliability.

In conclusion, embedded systems are not only technical components but also strategic enablers of the energy transition. Their continued advancement will be pivotal to unlocking the full potential of V2G and accelerating the global energy transition toward carbon neutrality.

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