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Challenges and Opportunities of Vehicle-to-Grid

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Abstract – Electric vehicles (EVs) are rapidly scaling and increasingly interacting with power and transportation systems, motivating a unified review of EV architectures, control, and vehicle-to-grid (V2G) services. This paper first classifies EVs as gridable or non-gridable from a distribution-operator perspective, then synthesizes key energy pathways, grid electricity with dominant lithium-ion and emerging sodium-ion/solid-state batteries, hydrogen fuel-cell routes, and dual-source configurations, and their implications for efficiency, emissions, and operating modes. Onboard energy management is reviewed as a layered framework spanning powertrain EMS and battery/thermal management, emphasizing constraint-aware, predictive, and learning-enabled control under high-power charging. The review then reframes V2G by interface technology, comparing wired and wireless V2G across accessories, systems, and operations. Major value streams (ancillary services, capacity deferral, demand-charge reduction, resilience) and deployment constraints (battery life, distribution impacts, cybersecurity, metering, economics, and standards) are consolidated. Finally, wireless EV energy networks are discussed, highlighting research needs in coupled energy routing and traffic-aware scheduling.

Keywords: Electric vehicles, Vehicle-to-Grid (V2G), Wireless power transfer, Wireless electric vehicle energy network

1. Introduction

Electric vehicles (EVs) are developing rapidly, and their integration with modern power and transportation systems requires a clear understanding of EV classifications, energy pathways, and control strategies. From the distribution network operators' perspectives, EVs can be classified as gridable and non-gridable EVs [1] [2] [3] [4]. With these EV types defined, the next step is to examine the energy sources that supply gridable and non-gridable EVs. For the EV energy sources, it covers grid electricity and diversified on-board or supporting energy pathways, including hybridized energy-source configurations that affect overall efficiency and operating modes [5] [6]. Building on the identified EV energy sources, EV energy management is then introduced as the decision-making and control framework that monitors battery states and schedules energy flow to satisfy mobility requirements while improving efficiency, reliability, and lifecycle performance through appropriate estimation, modeling, and management methods [7] [8].

As EV penetration increases, the concept naturally extends from vehicles as passive electrical loads to vehicle-to-grid (V2G) to participate in smart grid operations, which converts EVs into fast, distributed energy resources, but most reviews organize benefits and barriers by user type, individual EV versus EV fleet [9] [10] [11] [12]. This paper reframes the landscape around the interface technology itself, conductive (wired) and inductive (wireless) V2G, because interface characteristics largely determine technical feasibility, economics, and policy pathways. Wired V2G, enabled by mature bidirectional power converters, offers higher power levels, lower conversion loss, and clearer interconnection practice, therefore immediately suited to ancillary services and distribution-aware demand management. Wireless V2G trades some efficiency and rated power for frictionless, automated participation, and improved safety [13] [14]. These features can raise participation rates and effective capacity factors, especially for depots, campuses, and curbside contexts. A common services stack is first established, including V2G accessories [15] [16], V2G systems [17] [18], and V2G operations [19] [20] [21]. The opportunities of these services include ancillary services, capacity deferral, demand-charge reduction, and resilience enhancements, which are also investigated. The cross-cutting challenges and their interface-specific expressions are also reviewed for each sub-stack. For battery lifetime, both modalities require lifetime-aware control, including mid-state of charge cycling, bounded depth-of-discharge, temperature limits, but wireless systems must additionally manage coil alignment and thermal hotspots that can exacerbate degradation at high reactive currents [22]. Distribution-system impacts involve

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transformer loading, voltage deviations, and harmonics, which are common to both interfaces. Wired units can leverage established reactive power and filtering functions, whereas wireless systems must meet stricter electromagnetic interference and electromagnetic compatibility requirements, as well as foreign-object and heating constraints [23]. Communications, metering, and cybersecurity are essential enablers for market participation and settlement in both cases; wireless adds the need for alignment, telemetry, and safety interlocks [24]. Economic viability hinges on stacked revenues that come from regulation, capacity deferral, demand-charge reduction, and resilience enhancements. In contrast, the cost involves capital expenditures, operating expenses, and degradation for both models. Here, wired systems benefit from lower equipment cost per kilowatt and better round-trip efficiency, whereas wireless can recoup value via higher user uptake, automation, and siting flexibility [25]. As for policy and standards, they must clarify bidirectional interconnection, metering rules, and aggregator access; wireless V2G further requires field-exposure compliance and performance certification for misalignment and foreign-object scenarios [26]. Last but not least, an emerging concept of the wireless electric vehicle energy network (WEVEN) will also be discussed due to its increasing interest both in academia and industry [27].

The paper aims to provide a comprehensive review of both EV-related technologies and V2G services with interface constraints, serving as a reference architecture for both wired and wireless V2G in terms of challenges and opportunities across various technological and economic perspectives. And these opportunities and challenges are summarized in Fig. 1. Section 2 is a brief review of basic EV concepts, including EV types, EV energy sources, and EV energy management. Section 3 focuses on V2G accessories, systems, and operations. The wireless V2G and WEVEN will be investigated in Section 4. And this review is concluded with section 5.

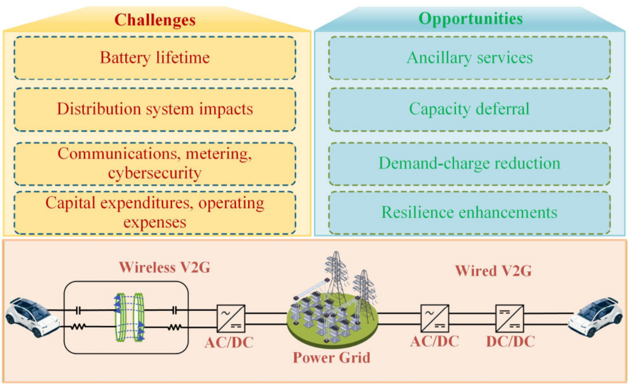

Figure 1. Opportunities and challenges of wired and wireless V2G

2. EV Architectures: Types, Energy Sources, and Energy Management Frameworks

2.1 EV Types

From the power utility operator's view, EVs can be classified as gridable and non-gridable EVs. Gridable EVs are introduced as vehicles whose charging (and potentially discharging) can be coordinated to support grid-level objectives through controllable charging profiles and grid-interactive functions, whereas non-gridable EVs are treated as user-driven or operationally constrained participants with limited controllability from the grid perspective [28]. More specifically, in practice, gridable EVs align with managed/smart charging: the time and rate of charging are actively controlled (often unidirectional) to provide grid services such as load shifting and peak shaving; with bidirectional capability, they can extend to V2X/V2G power export [29]. By contrast, non-gridable EVs typically follow unmanaged charging ("plug in and charge"), which can cluster at residential arrival times, create new demand spikes, and stress local distribution assets when many EVs charge simultaneously [30].

2.2 EV Energy Sources

Grid electricity (for battery electric vehicles (BEVs) and plug-in electric vehicles (PHEVs) remains the dominant energy source for most "electric-drive" vehicles: energy is delivered from the power system to the vehicle through charging interfaces (AC and DC), and its lifecycle emissions depend strongly on the generation mix and the pace of grid decarbonization. The International Energy Agency explicitly highlights that cleaner grids amplify BEV benefits, while the Alternative Fuels Data Center summarizes that BEVs/PHEVs draw electricity from the grid (and other off-board electrical sources) as their primary refueling pathway [31]. Batteries (electrochemical storage inside the vehicle) convert that electricity into usable traction energy; consequently, battery chemistry choices shape cost, safety, energy density, and supply-chain exposure. In today's market, lithium-ion chemistries dominate, with widely used families including Lithium Iron Phosphate (often emphasized for safety/cost and lower reliance on nickel/cobalt) and Nickel Manganese Cobalt/Nickel Cobalt Aluminum (often emphasized for higher energy density and vehicle range) [32]. Moreover, emerging battery pathways are increasingly discussed as additional EV "energy-source enablers" because they can change how electricity is stored onboard. Two prominent directions are: (1) sodium-ion batteries, positioning as lower-cost and less lithium-dependent options (now moving toward broader commercialization claims) [33], and (2) all-solid-state batteries, targeting higher safety and potentially higher energy density, but still facing manufacturing and durability barriers [34].

Hydrogen (for fuel-cell electric vehicles) is a distinct off-board energy carrier: the vehicle is electrically propelled, but electricity is generated onboard by a fuel cell using stored hydrogen. The key differentiator is that the upstream pathway (electrolysis vs. fossil-based hydrogen, delivery, and compression/liquefaction) governs climate and cost performance; it is noted that low-emissions hydrogen remains a small fraction of total production, underscoring the "pathway constraint" for large-scale transport use. In energy-efficiency terms, recent synthesis work finds direct electrification is typically substantially more efficient than green-hydrogen-to-mobility pathways, which has planning implications for prioritizing hydrogen in harder-to-electrify segments [35].

Dual-source electric-drive pathways (PHEVs and range-extended EVs) draw energy from both grid electricity and liquid fuels. PHEVs use a battery and electric motor but also carry a conventional fuel (commonly gasoline, sometimes diesel or alternatives), with operating modes that blend or switch between electric propulsion and engine support [36]. Range-extended configurations similarly pair an electric drivetrain with an onboard fuel-powered generator intended primarily to recharge/maintain the battery rather than directly drive the wheels. These architectures broaden refueling flexibility but reintroduce upstream fuel emissions and operational dependence on charging behavior (how often drivers plug in) [37]. Also, some "supplemental" sources are best treated as secondary contributors rather than primary EV energy sources. Regenerative braking recovers kinetic energy that would otherwise be lost (improving overall efficiency), but it does not replace the need for an external refueling pathway [38]; likewise, onboard solar can provide marginal auxiliary energy in certain duty cycles but is typically not a core propulsion energy source for mainstream passenger EV operation [39].

2.3 EV Energy Management

EV energy management spans onboard control (how the vehicle uses and preserves energy while driving) and offboard coordination (how/when it exchanges energy with chargers, buildings, and the grid). This sub-section focuses on the discussion of onboard control, and the offboard coordination will be addressed in the subsequent sections as V2G. At the powertrain energy management strategy (EMS) layer, the controller allocates propulsion and recuperation power to minimize energy use (or maximize range) while meeting torque demands and respecting actuator and battery constraints. For BEVs, especially dual-motor architectures, EMS is often framed as a constrained optimal control problem whose "decision variables" include motor torque split, operating points, and regenerative braking blending, because these choices strongly affect drivetrain efficiency and losses [40]. A common way to organize powertrain EMS methods is: (i) rule-based strategies (calibration-heavy but robust and computationally light), (ii) optimization-based strategies (e.g., model predictive control (MPC)/dynamic programming surrogates) that explicitly handle constraints and look-ahead, and (iii) learning/predictive strategies (e.g., reinforcement learning) intended to improve adaptability to varying routes, traffic, and driver behavior. Recent reviews and comparative studies emphasize that MPC and reinforcement learning approaches are typically motivated by the need for real-time feasibility under constraints and improved generalization beyond fixed heuristics [41]. For dual-motor BEVs, a core EMS subproblem is optimal torque split: distributing wheel torque between motors (and possibly axles) to keep each machine near its high-efficiency region, while honoring traction limits and drivability. The EMS design process in this setting usually includes (a) powertrain modeling and efficiency-map utilization, (b) constraint definition (motor/inverter limits, battery power limits), and (c) real-time implementable control logic [42].

At the battery management layer, the battery management system (BMS) provides the "health and safety envelope" for the entire vehicle by monitoring pack variables and enforcing limits on charge/discharge power. Core BMS functions typically include state-of-charge (SOC) estimation, state-of-health tracking, protection/safety logic, and cell balancing, because inaccurate states or unbalanced cells can force conservative limits or accelerate degradation [43]. The battery thermal management system (BTMS) is tightly coupled to BMS and powertrain EMS because temperature directly constrains usable power, charging acceptance, aging rate, and safety margins. It can be noted that high temperatures accelerate degradation, while low temperatures reduce power and energy capability, motivating BTMS designs that keep cells within a preferred operating range. In terms of thermal management approaches, they are commonly classified into families such as air cooling, liquid cooling, phase-change-material-based solutions, and other advanced concepts, each with characteristic trade-offs in heat removal capability, complexity, parasitic energy use, and cost. Fast charging and high-power duty cycles intensify thermal constraints, making the BTMS/EMS interaction more consequential: EMS decisions that raise battery current may reduce drivetrain losses but can become infeasible once thermal limits are active, so many modern strategies increasingly treat thermal and aging constraints as first-class constraints rather than afterthoughts [44].

3. V2G Enabling Technologies and Operational Strategies

3.1 V2G Accessories

V2G hardware accessories go beyond a standard charger: bidirectional electric vehicle supply equipment (EVSE) typically adds inverter-grade power conversion plus grid-interface elements (contactors, insulation/ground-fault monitoring, sensing, thermal management) and often protection/telemetry consistent with distributed energy resources (DER)-style interconnection expectations. These accessories exist to make "export" (discharging) as controllable and safe as "import" (charging) [45]. V2G communications accessories are the embedded controllers, gateways, and protocol stacks that coordinate schedules, limits, and authorization across the end-to-end chain: EV and EVSE messaging for bidirectional power transfer (International Organization for Standardization(ISO) 15118-20), DC charging/discharging control communications (International Electrotechnical Commission(IEC) 61851-24), and EVSE to backend interoperability for managed charging and ISO-15118 integration (Open Charge Point Protocol(OCPP) 2.0.1 ecosystem). V2G metering/settlement accessories must support bi-directional energy accounting and auditable billing: implementations commonly use revenue-grade submeters (embedded or external), plus time sync and tamper-evident logging. Meter accuracy and test regimes are often discussed via American National Standards Institute C12.20 (North America) and legal metrology frameworks such as International Organization of Legal Metrology R46 for active energy meters [46]. Besides, V2G cybersecurity accessories include secure credential storage, certificate/public key infrastructure operations, hardened communications, and patch/monitoring processes, often aligned with Operational Technology/Industrial Automation & Control Systems security frameworks and smart-grid cybersecurity guidance (National Institute of Standards and Technology Internal or Interagency Report (NISTIR) 7628) [47]. Cost-wise, capital expenditure is driven by bidirectional EVSE and the add-ons above (protection, metering, secure comms, interconnection/commissioning); operating expenses are dominated by connectivity and charging station management system fees, maintenance/calibration, certificate lifecycle management, and continuous security operations. The National Renewable Energy Laboratory (NREL) reports an illustrative estimate of $4,500–$5,500 for a 10 kW bidirectional EVSE unit, underscoring hardware cost as a key barrier [48].

3.2 V2G Systems

V2G systems are typically discussed under vehicle–grid integration (VGI), where EV charging/discharging is coordinated (time, power level, location) to benefit the grid while meeting mobility needs. This includes managed charging (V1G) and bidirectional modes such as V2H/V2B (behind-the-meter) and V2G (grid/market-facing), which differ mainly in objectives and compliance burden [49]. At the power-interface level, V2G implementations often separate into AC-coupled and DC-coupled architectures. DC-coupled approaches frequently adopt a DC bus/DC microgrid concept to integrate PV/storage and EVSE with fewer conversion stages, an increasingly studied topology for high-power charging hubs and coordinated site operation [50].

Standards ecosystems are central to "which V2G system" is feasible. CHAdeMO has long positioned bidirectional (V2X/V2G) as a core capability, while newer roadmaps emphasize a combined charging system with ISO 15118-20, which defines message sequencing for bidirectional power transfer. For conductive DC systems, IEC 61851-24 (with IEC 61851-23) specifies digital communication between DC EVSE and the vehicle for control of DC charging/discharging [51]. Operationally, scalable V2G is commonly a three-layer control stack: (i) EV to EVSE session negotiation and limits, (ii) EVSE to backend station management/dispatch, and (iii) aggregator/utility interface for grid services and settlement. OCPP is widely used for the EVSE-to-central-system link to enable multi-vendor interoperability and coordinated charging control at scale [52]. By deployment context, V2G systems are usually grouped as residential vehicle-to-home (V2H)/vehicle-to-building (V2B), commercial building V2B, and fleet/depot V2G, with fleets attractive due to predictability and simpler aggregation [53]. Grid-facing deployments typically must align with DER interconnection/interoperability requirements (e.g., IEEE 1547-2018) and a smart-grid cybersecurity posture (e.g., NISTIR 7628 guidance) [54].

3.3 V2G Operations

V2G operations are usually organized as managed charging (V1G), behind-the-meter bidirectional operation (V2H/V2B), and grid/market-facing bidirectional operation (V2G). V1G primarily reshapes charging to meet price and network constraints (e.g., peak shaving, load shifting, demand response), while V2H/V2B adds export to serve onsite objectives, and V2G extends dispatch to external grid-service requests with tighter telemetry, baselining, and performance verification requirements [55] [56]. For ancillary services, the most-cited operational pathway is aggregation for fast, inverter-like products such as frequency regulation and operating reserves, where portfolios of EVs can provide up/down capability (charging for "down," discharging for "up") in response to control signals [57]. At scale, this is commonly implemented via an aggregator that bids a fleet as one resource; in the U.S., Federal Energy Regulatory Commission (FERC) Order 2222 directs Regional Transmission Organizations to enable DER aggregations to participate in organized wholesale markets, and FERC Order 841 targets the removal of barriers for electric storage participation in those markets [58]. For capacity deferral, "beneficial VGI" operations prioritize local constraint relief: shifting charging away from feeder/transformer peaks (V1G) and, where permitted, exporting during stressed periods (V2G/V2B) to reduce coincident peaks and defer distribution upgrades. This is often framed as a grid-reliability and resilience measure contingent on proper coordination across the EV–EVSE–grid ecosystem [59]. For demand-charge reduction, the dominant operational pattern is V2B peak shaving (and/or carefully scheduled charging) to cap a facility's monthly peak demand, since many commercial tariffs bill demand charges based on the month's highest demand interval. NREL explicitly highlights demand-charge mitigation as a key V2G value stream and reports field evidence of measurable peak-shaving value when adequate export power is available [60]. For resilience enhancements, bidirectional EVs are operated as mobile backup storage for critical loads (homes/buildings) and can be integrated into microgrid-style strategies alongside other DER; the Department of Energy further notes potential roles in emergencies and even possible assistance to black-start restoration concepts [61].

These operations are constrained by battery lifetime (incremental cycling, SOC swing, C-rate, temperature, and warranty/compensation alignment) [62] and by distribution-system impacts (transformer loading, voltage deviations, protection/coordination, and hosting capacity) [63]. Some V2G program designs may extend battery life under certain conditions, while broader literature emphasizes that degradation outcomes are program- and context-dependent; similarly, empirical/economic analyses warn that even a few coincident fast-charging events can overload neighborhood transformers, motivating distribution-aware dispatch and monitoring [64]. Also, policy and rules largely determine feasible operations: interconnection/interoperability expectations often align with IEEE 1547-2018-style DER practices, implemented through state tariffs such as California Rule 21; market-access pathways in the U.S. are shaped by FERC Orders 2222 and 841; and program-specific provisions can matter, for example, Southern California Edison documents Rule 21 testing/certification guidance and an exemption pathway used to enable DC V2G EVSE participation in California's Emergency Load Reduction Program under specified conditions. In the European Union (EU), the Alternative Fuels Infrastructure Regulation (Regulation (EU) 2023/1804) is a binding framework for alternative-fuels infrastructure deployment that also influences interoperability and smart-charging expectations relevant to V2G scale-up [65]. The figure that depicts the V2G ecosystem map is illustrated as Fig. 2.

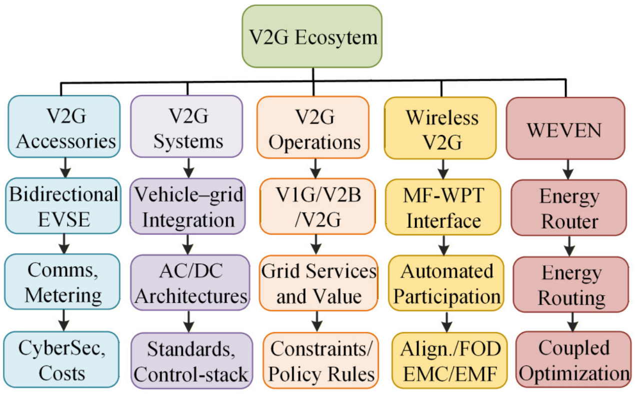

Figure 2. V2G ecosystem map

4. Wireless V2G and WEVEN

4.1 Wireless V2G

Wireless V2G is typically realized with magnetic-field wireless power transfer (MF-WPT) using resonant inductive couplers ("ground assembly" pad and "vehicle assembly" receiver). For bidirectional operation, the vehicle side generally moves from a passive rectifier to an active rectifier/inverter, so real power can be driven in either direction by phase/control of the resonant converters and the grid interface [66]. The MF-WPT interface characteristics are commonly expressed via self-inductances, mutual inductance, and coupling coefficient [67]. The transferred power is typically written in forms that make the interface dependence explicit (e.g., scaling with mutual inductance and converter phase shift), while misalignment and air gap are modeled as reductions in mutual inductance (hence coupling coefficient), shifting the operating point and reactive circulation in the compensated network (Series-Series/Series-Parallel/Inductor-Capacitor-Capacitor families are widely used). Standards anchor this interface to a defined operating band (e.g., ISO 19363 specifies operation within 79–90 kHz for onboard components), enabling interoperable pairing and repeatable test conditions [68]. On rated power and efficiency, Society of Automotive Engineers (SAE) J2954 structures light/medium-duty wireless charging into discrete WPT power levels (e.g., WPT1–WPT5 spanning 3.7 kW to 50 kW, depending on revision/vehicle class) [69]. Reported targets highlight the sensitivity to interoperability: J2954-aligned targets of >85% (matched coils) and >80% (interoperable coils) for lower power classes, while also showing that coil-to-coil efficiency can be much higher under good alignment and compensation, meaning system efficiency becomes dominated by inverter/rectifier losses, thermal limits, and electromagnetic interference (EMI)/electromagnetic compatibility (EMC) constraints as power increases [70].

The principal operational advantage of wireless V2G is frictionless, automated participation: no plug handling, reduced user effort, and easier integration into autonomous/assisted parking workflows, factors often cited as improving real-world uptake for smart charging/V2G programs [71]. This depends on telemetry and coordination across the EV, pad, and backend: IEC 61980-2 is explicitly scoped to MF-WPT communication and "activities" plus positioning functions, while IEC 61980-3 requires (as part of the off-board equipment scope) characteristics/operating conditions and basic communication for safety/process matters plus positioning to assure efficient and safe transfer [72]. Wireless V2G also changes the safety and reliability envelope. It removes exposed conductive contacts but introduces stricter needs for foreign-object detection (FOD), living-object protection, safety interlocks, and defined shutdown behaviors under abnormal conditions [73]. A detailed FOD review notes SAE J2954 calls for both metal object detection and living object detection, including specified sample objects and temperature-rise/ignition-oriented tests, because metallic debris can form localized eddy-current heating and create thermal hotspots [74]. These requirements become more binding in bidirectional/high-power modes, where loss density rises in coils, ferrites, and nearby conductors, intensifying thermal management challenges. Moreover, alignment and EMC/Electromagnetic field compliance are the dominant certification drivers for wireless V2G. Misalignment is typically parameterized as linear offsets and angular roll/pitch/yaw; SAE-aligned discussion reports representative expectations such as linear offsets (75mm horizontally and 100mm vertically) and angular tolerances (roll/pitch ±2°, yaw ±10°), which directly degrade coupling and can increase leakage fields and heating [75]. IEC 61980-3 explicitly includes positioning and specific EMC requirements, and SAE J2954 includes recommended methods for evaluating electromagnetic emissions and alignment methodology, so qualification is not only "best-alignment performance," but performance and safety under misalignment and foreign-object scenarios [76]. On field exposure, NREL's in-vehicle measurements (including misalignment cases) compare results against International Commission on Non-Ionizing Radiation Protection/IEEE reference levels and report adherence at test points, illustrating the kind of evidence expected for field-exposure compliance when deploying wireless V2G at scale [77].

4.2 WEVEN

By considering the EV wireless V2G from a network perspective, the concept of WEVEN was raised. The WEVEN extends the "Vehicular Energy Network (VEN)" idea [78] by using EV mobility plus dynamic wireless (dis)charging to route electrical energy through a traffic network, not just to refuel vehicles [79]. In typical formulations, selected road segments and junctions are electrified so EVs can charge and discharge wirelessly while moving, enabling "energy packets" to be injected/extracted along multi-hop vehicular routes [80]; junctions may be modeled as wireless energy routers that coordinate bidirectional WPT sessions and local buffering to facilitate multi-source–multi-destination energy transport and even localized energy trading [81]. This turns system operation into a coupled problem of energy routing + vehicle routing/energy scheduling under SOC constraints, traffic flows, and economic signals (prices/incentives), with studies demonstrating feasibility and profitability potential under realistic traffic data assumptions [82]. The reference architecture of wired/wireless V2G and WEVEN, showing energy flow, control/communications, constraints, and standards are depicted in Fig. 3.

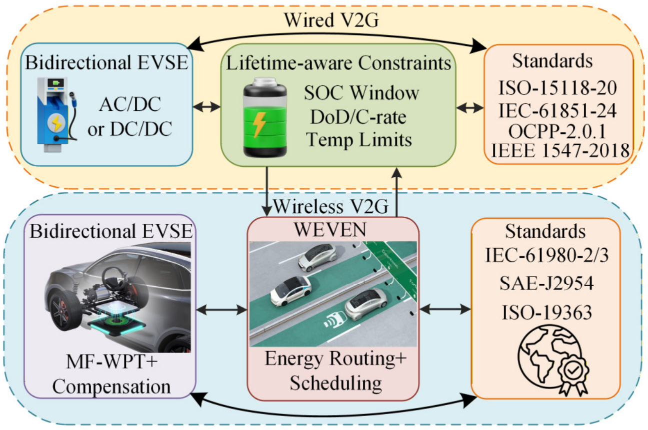

Figure 3. Architecture of wired/wireless V2G and WEVEN

5. Conclusion

This review synthesized EV–grid integration (V2G) from operator and interface perspectives. It first defined gridable vs. non-gridable EVs, then summarized key energy pathways, highlighting how upstream pathways and charging behavior shape efficiency, emissions, and grid impacts. It also framed EV energy management as layered control. The core contribution is organizing V2G by interface technology, wired (conductive) versus wireless (inductive), since interface characteristics govern feasible services, costs, certification, and deployment. Across accessories, systems, and operations, it consolidated major value streams and key barriers. Wired V2G is typically advantaged in power/efficiency with clearer interconnection practice, while wireless V2G can raise participation and siting flexibility but must meet stricter alignment, FOD, thermal-hotspot, and EMI/EMC requirements with verified performance under misalignment and foreign-object conditions. Finally, WEVEN was discussed as an emerging extension where dynamic wireless (dis)charging enables energy routing/trading over transport networks, motivating coupled research in routing, traffic-aware control, and market design. It is anticipated that this V2G technology will become a major EV research direction, and soon be translated into EV education [83] [84].

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