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Article

# Review of Electric Vehicle Charging Stations and Battery Management Systems with Solar Integration

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**Abstract:** The shift to electrified road transport has put electric vehicle (EV) charging infrastructure, battery management systems (BMS), and integration of renewable-energy sources in the heart of modern energy and transportation science. This review is an overview of the existing body of knowledge in three closely related areas: (i) EV charging infrastructure, such as charging levels, connector standards, station architectures, and communication protocols; (ii) battery management systems, such as battery chemistries, state-of-charge (SOC) and state-of-health (SOH) estimation, cell balancing, and thermal management; and (iii) combining solar photovoltaic (PV) generation with EV charging stations, such as system topologies, maximum power point tracking (MPPT), power-electronic interfaces, and energy management strategies. The review emphasizes the potential of solar-integrated charging stations, which with intelligent BMS and energy management controllers, can decrease grid reliance, decrease operating expenses, and enhance the sustainability profile of EV charging. The important trade-offs in the technical aspects are summarized in two comparison tables of charging levels and SOC estimation techniques, and two illustrative plots of a typical solar-EV-BMS system structure and power curves of solar and demand per day. The review ends by listing the unresolved issues, such as battery degradation during fast charging, PV intermittency, standardization, and cybersecurity, and providing new research opportunities, such as artificial-intelligence-based energy management, vehicle-to-grid (V2G) operation, second-life battery storage, and predictive maintenance provided by digital twins.

**Keywords:** - EV Charging Infrastructure, Battery Management System, State of Charge Estimation, Solar PV Integration, MPPT, Vehicle-to-Grid (V2G), Energy Management Strategy

## 1. Introduction

The need to decarbonize the transportation sector has resulted in a rapid growth in the uptake of electric vehicles (EVs) in the last ten years across the globe. An increasing environmental consciousness, stricter emissions standards, and a rapidly increasing battery-energy density and cost have all come together to make EVs an acceptable alternative to internal combustion engine (ICE) vehicles. Yet, the large-scale transition to EVs may be subject to two intertwined facilitators: a reliable and convenient charging network, and a battery control system that will be able to guarantee the safety, durability, and functionality of the underlying battery pack. The potential of electrified mobility cannot be achieved in full without the presence of strong charging networks and a dependable battery management.

There are various paths that have been developed in EV charging infrastructure. Charging at homes and workplaces usually uses Level 1 and Level 2 alternating-current (AC) devices, with public highway networks and commercial fleet depots adopting direct-current (DC) fast and ultra-fast chargers that can restore hundreds of kilometers of range in minutes. It has been complemented by an expansion of connector standards (SAE J1772, CCS, CHAdeMO, GB/T and, more likely to succeed in the market, the North American Charging Standard, NACS), communication protocols (ISO 15118, OCPP), and business models (public charge-point operators, subscription networks, workplace charging and battery-swap stations).

Simultaneously, the battery pack, most often with a lithium-ion chemistry, must be continuously monitored and regulated to stay within safe voltage, current and temperature ranges. This function is carried out by the battery management system which determines state of charge (SOC) and state of health (SOH), balancing the individual cells in a series-connected pack, thermal conditions, and communication with the vehicle control unit and, more and more, with the charging infrastructure itself. The lithium-ion cells can be overcharged, over-discharged, and overheat; therefore, the BMS is not a luxury but a safety-critical subsystem directly influencing the range that the vehicle can be used and the long-term battery degradation.

The third and possibly the most significant dimension is the combination of renewable energy most often solar photovoltaic (PV) generation with EV charging infrastructure. The charging of a large EV fleet solely along the traditional grid might overload distribution networks, especially when numerous vehicles are being charged at the same time during peak demand times. Solar-integrated charging stations, grid-tied, standalone, or hybrid, provide an avenue to this load reduction, decreasing the carbon intensity of the charging, and, in certain models, to provide backup power and grid-support services. These advantages come with the caveats, though, of needing to co-design the PV array, power-electronic converters, an intermediate storage buffer (often a stationary battery), and an energy management controller that will coordinate the flow of power between the solar source and the grid, the stationary storage and the EV battery, and which must take into account the operating constraints of the vehicle-supplied BMS.

This transition has been very fast. Reporting by industries and institutions show that the number of EVs sold worldwide increased between about 10 million units in 2022 and about 14 million units in 2023, and is expected to go beyond 17 million units in 2024, owing to the decreasing prices of batteries, the development of more charging networks, and supportive policy in Europe, China, and North America. This trend puts long-term pressure on the planning of charging infrastructure, distribution-grid capacity, and the pipeline of raw materials and manufacturing capacity to supply EV battery packs, further reaffirming the practical significance of the technical themes discussed in this paper: efficient charging infrastructure, safe and durable battery management, and integration with renewable energy capable of absorbing the increasing charging demand without excessively straining the grid.

The three strands of literature discussed in this review paper, namely charging infrastructure, battery management systems, and solar integration, are synthesized, to a single and organized review paper. Section 2 examines EV charging infrastructure, such as the levels of charging, the standards, and the architecture of the stations. Section 3 discusses battery technologies and management systems, and focuses on SOC/SOH estimation and cell balancing as well as thermal management. Section 4 presents the combination of solar PV generation and EV charging including the system configurations and MPPT methods. Section 5 provides the design of along with energy management of an integrated solar-EV-BMS system, and provides examples. The open challenges are discussed in Section 6, future research directions are outlined in Section 7, and the review is concluded in Section 8.

## 2. EV Charging stations.

One can broadly categorize EV charging infrastructure based on the level of power, the type of current (AC or DC), physical connector standard and the ability to communicate. This part explores all these dimensions and presents typical charging-station architectures.

### *2.1 Charging Levels and Standards*

Traditionally, charging devices are classified as Level 1, Level 2, and Level 3 (DC fast charging) and a new category is ultra-fast or high-power DC charging over 150 kW. Level 1 charging is either a regular household single-phase outlet and provides about 1.4-1.9 kW, which is applicable mainly to overnight residential charging with the vehicle parked overnight. Level 2 charging, which is supplied by specific AC equipment at 208-240 V, has 3.3-19.2 kW and is the most popular type of home, workplace and destination charging. DC fast charging does not use the vehicle onboard charger but converts AC to DC in the off-board charging unit, and directly powers the battery at a higher rate of 50-350 kW and more bypassing the vehicle onboard charger, which saves a significant amount of time; however, more complex power electronics, thermal management, and grid interconnection infrastructure are needed.

A number of local standards exist that regulate the physical connector and communication interface between the charger and the vehicle. The Combined Charging System (CCS1) has long been employed in North America to combine DC fast charging with the SAE J1772 connector to AC, but the industry has been quickly moving towards the Tesla-designed NACS to provide both AC and DC charging. CSS2 (with the Type 2 AC connector) is the standard in Europe. One of the early DC fast-charging standards was Japan's CHAdeMO standard, and the Chinese uses the GB/T standard dissimilarly on both AC and DC charging. In the case of heavy-duty vehicles, a Megawatt Charging System (MCS) is being developed to handle charging at power rates in to the megawatts range to allow the quick turnover of electric buses and trucks.

| **Charging Level** | **Typical Power / Voltage** | **Current Type** | **Approx. Charge Time (0-80%, ~60 kWh pack)** | **Common Connectors** | **Typical Application** |
|---|---|---|---|---|---|
| Level 1 (AC) | 1.4 - 1.9 kW; 120 V, 12-16 A | Single-phase AC | 20 - 40 hours | SAE J1772, Type 1 | Residential trickle charging |
| Level 2 (AC) | 3.3 - 19.2 kW; 208-240 V, up to 80 A | Single/three-phase AC | 4 - 10 hours | SAE J1772, Type 2 (IEC 62196), GB/T AC | Home, workplace, public AC posts |
| Level 3 / DC Fast Charging | 50 - 150 kW; 400-600 V DC | DC (off-board converter) | 0.4 - 1.5 hours | CCS Combo 1/2, CHAdeMO, GB/T DC, Tesla NACS | Highway corridors, fleet depots |
| Ultra-Fast / High-Power DC | 150 - 350+ kW; up to 1000 V DC | DC (off-board converter) | 0.15 - 0.6 hours | CCS2, NACS, Megawatt Charging System (MCS, heavy duty) | Flagship highway hubs, heavy-duty trucks |
| Wireless / Inductive | 3.3 - 11 kW (static); up to 20 kW (dynamic, trial) | AC (resonant induction) | Comparable to Level 2 | SAE J2954 (emerging) | Static parking pads, pilot dynamic-road charging |

Table 1. Comparative overview of electric vehicle charging levels, typical power ratings, connector standards, and applications (illustrative figures compiled from published technical literature; actual values vary by vehicle, charger, and grid conditions).

### *2.2 AC vs DC Charging Architectures.*

The basic difference between the AC and DC charging is in the location of the ACto-DC conversion of power. In AC (Level 1 and Level 2) charging, the onboard charger rectifies the charging current to the battery and regulates the current that is sent to the battery; this makes the equipment at the roadside or on the wall simple and affordable but restricts the charging power to that which the onboard charger can accommodate, usually a few kilowatts to about 19 kW. The conversion of AC to DC and the regulation of voltage in DC fast charging is done in off-board charging unit, and much higher power levels can be delivered directly to battery terminals, as the size and cooling needs of an off-board charger are much less constraining than the size and cooling of an onboard charger. The reason why DC fast chargers are necessary to facilitate long distance travel and quick turnover at both commercial and fleet charging locations is this difference in architecture.

### *2.3 Architecture and topologies of charging stations.*

Newer EV charging stations are designed to utilize a common DC bus design, where the grid connection, on-site renewable generation, stationary battery storage and the EV charging outlets are all connected to a common DC bus via dedicated power-electronic converters. This topology has the benefit of simplifying the control of power flow, fewer conversion stages between natural DC sources (solar PV and batteries) and DC loads (EV battery charging) using it, and allows power to flow both ways in vehicle-to-grid (V2G) and vehicle-to-home (V2H) applications. Some other architectures such as AC-coupled, where individual sources are connected to a shared AC bus via their own inverter, provide easier integration with the present AC distribution infrastructure, at the cost of further conversion losses where power must pass between DC sources and DC loads.

The placement of onboard and off-board converters, the ability to flow in a unidirectional or bidirectional direction and the ability to be either single-port or multi-port all characterize charging station topologies, whose onboard or off-board converter placement allows several vehicles to share a common power-electronic front end and dynamically allocate available power to connected vehicles based on their state of charge and charging priority.

### *2.4 Smart Charging and Communication Protocols.*

Smart charging is based on the standardized communication between the vehicle, the charging station and the backend management system. The ISO 15118 standard is used to authenticate plug-and-charge and complete the two-way power negotiation needed to run V2G, and the Open Charge Point Protocol (OCPP) regulates the communication between charging stations and central management systems to perform a variety of functions, including remote monitoring, load balancing, billing, and firmware updates. Combined, these guidelines enable charging networks to adopt demand-dependent charging schedules, dynamically restrict or relocate charging load to prevent grid congestion, and coordinate distributed charging stations as an aggregated, dispatchable resource - a feature that is especially useful when charging stations are also outfitted with on-site solar generation and storage, as mentioned in Section 4.

## 3. Battery Technology and Battery management systems.

The most costly and performance-important part of an EV powertrain is the battery pack. This part will discuss typical EV battery chemistries, fundamental operations of the battery management system and the main methods to estimate SOC/SOH, cell balancing, and thermal management.

### *3.1 EV Battery Chemistries*

The present EV market is dominated by battery cells based on lithium ion, which has a good balance of high energy density, high power density, low self discharge and relatively long cycle life. Among the lithium-ion family, nickel manganese cobalt oxide (NMC) and nickel cobalt aluminum oxide (NCA) chemistries have high energy density, and are being actively used in longer-range passenger vehicles, whereas lithium iron phosphate (LFP) chemistries have lower energy density, but better thermal stability, cycle life, and reduced cobalt and nickel dependence, becoming more popular in standard-range passenger vehicles and stationary storage. New chemistries like lithium-sulfur and solid-state batteries are developing additional increases in energy density and safer operation, but are at a lower level of commercial maturity.

### *3.2 Functions and Architecture of the Battery Management System*

A BMS will perform the following functions: provide continuous monitoring of cell-level voltage, pack current and temperature; estimate SOC, state of health (SOH) and state of power (SOP); implement safe operating limits by overvoltage, undervoltage, overcurrent, and overtemperature protection; balance charge between series connected cells; and communicate with the vehicle control unit and, where present, the charging infrastructure. The BMS is normally seen as a series of cell-monitoring modules or slave boards spread throughout the battery pack, a central master controller which combines the measurements and runs estimation and protection algorithms, and a communication bus usually a Controller Area Network (CAN) or Local Interconnect Network (LIN), which connects the BMS to the rest of the vehicle electronic control units.

### *3.3 State of Charge/State of Health Estimation.*

The correct estimation of SOC is at the core of the BMS operation since it directly relates to the reported range of the vehicle, can be used to decide on charging and discharging controls and can be used to help avoid the damaging overcharge or over-discharge events. The most basic method, coulomb counting, measures current cumulatively with time, but is susceptible to cumulative drift due to sensor bias and must be regularly recalibrated, e.g. by measuring open-circuit voltage (OCV). The model-based techniques, such as the extended and unscented Kalman filter, sliding-mode observers, and H-infinity filters, are model-based self-correcting, noise-resistant methods that do not have to spend long rest periods but use real-time sensor data to estimate a battery based on an equivalent-circuit or electrochemical battery model without the need to identify and track battery parameters. Electrochemical impedance spectroscopy (EIS) is highly diagnostic of internal battery conditions but is mostly limited to laboratory characterization over a one-off instrumentation cost and complexity. More modern, data-driven and machine-learning methods, such as artificial neural networks, long short-term memory (LSTM) networks, support vector machines and hybrid fusion models, have demonstrated high SOC and SOH estimation accuracy, but at the expense of large, representative training data sets and more onboard computational resources.

SOH estimation, a measure of how capacity and internal resistance of a battery change over time compared to its initial state at the beginning-of-life, has similar methodological lines. Capacity-based and incremental-capacity-analysis approaches monitor changes in characteristic voltage parameters during charging in order to estimate degradation and data-driven SOH models are becoming more common in using partial-charge voltage curves to not require full charge-discharge cycles, which is a key practical consideration since EVs are hardly ever exercised between empty and full under controlled conditions.

| **Estimation Method** | **Operating Principle** | **Key Advantages** | **Key Limitations** | **Typical Reported Accuracy** |
|---|---|---|---|---|
| Coulomb Counting (Ah Integration) | Integrates measured current over time relative to rated capacity | Simple, low computational cost, real-time capable | Drifts with sensor bias/noise; needs periodic re-calibration | ~5% (short term) |
| Open-Circuit Voltage (OCV) | Maps relaxed terminal voltage to SOC via a pre-characterized OCV-SOC curve | Conceptually simple; good for calibration/offset correction | Requires long rest periods; curve is flat in mid-SOC region for LFP cells | Moderate, rest-dependent |
| Model-Based Filtering (EKF/UKF, Sliding Mode, H-infinity) | Fuses an equivalent-circuit or electrochemical model with sensor data via recursive state estimation | Self-correcting, robust to noise, works online without rest | Model-parameter dependent; tuning complexity; aging sensitivity | ~1-3% |
| Electrochemical Impedance Spectroscopy (EIS) | Analyzes frequency-domain impedance response to infer internal states | Rich diagnostic information; useful for SOH and degradation analysis | Expensive instrumentation; not yet practical for continuous onboard use | High (lab-grade) |
| Data-Driven / Machine Learning (ANN, LSTM, SVM, Fusion) | Learns nonlinear mapping from voltage/current/temperature histories to SOC/SOH | Captures nonlinear aging effects; improves with more data; no explicit battery model needed | Needs large, representative training data; limited extrapolation; higher compute load | ~0.5-2% (reported) |

**Table 2. Comparative summary of common state-of-charge (SOC) estimation methods used in EV battery management systems.**

## *3.4 Cell Balancing Techniques*

Since EV battery packs are hundreds of series and parallel-linked cells, tolerances in manufacturing and nonuniform thermal environments inevitably lead to small capacity and internal resistance variability in cells. When uncorrected, the differences will grow through repeated cycles to a state of significant imbalance in the SOC of the entire pack, and this imbalance will reduce the usable capacity of the entire pack to that of the weakest cell and may lead to early degradation or early activation of safety measures. Passive balancing methods absorb unwanted energy in more advanced cells in the form of heat using a resistor, providing low cost and easy implementation at the cost of wasted power and increased heat. Active balancing methods rather shift charge between higher-SOC and lower-SOC cells via capacitive, inductive, or transformer-based circuits to enhance the energy efficiency and balancing speed, but at the cost of increased hardware cost and complexity of control. Balancing strategies, as machine-learning-aided and hybrid, combining passive simplicity with active-balancing decision logic, have been suggested to find a viable compromise between cost, efficiency and pack longevity.

## *3.5 Thermal Management*

Battery thermal management systems (BTMS) stabilize both the cell temperatures within the window of reliable and efficient operation of lithium-ion chemistries, typically 15-35 C, and also reduce temperature differences across the pack that would otherwise cause non-uniform aging. The simplest and lowest cost method is air cooling but has a lower heat-rejection capability and is only applied to lower-power applications. In liquid cooling, where the coolant is pumped into cold plates or channels in contact with the cells or modules, the capability of the coolant is significantly greater, and is now standard in most fast-charging-capable EVs. Phase-change materials (PCM) and PCM-liquid systems offer further passive thermal buffering when transiently subjected to a high-load event, like DC fast charging. Since thermal runaway, exothermic reaction, which is self-accelerating and can spread between cells, is one of the gravest safety hazards in lithium-ion battery packs, the BTMS is closely coordinated with the BMS voltage and temperature monitoring capabilities to identify warning signals and take protective measures before a localized failure can develop.

## 4. EV Charging Infrastructure with Solar Photovoltaic.

Combining EV charging stations with solar PV generation minimizes the use of grid electricity, decreases the effective carbon intensity of charging, and (with the right design of systems) can offer some resilience to the power supply in case of grid outages. This part presents typical system setups, MPPT approaches, and power-electronic system integrating PV generation, storage, the grid, and the EV battery.

### *4.1 System Configurations: Grid-tied, stand-alone, and hybrid.*

The grid-tied solar EV charging systems connect a PV array to the utility grid via a bidirectional inverter, enabling the station to acquire additional power when solar generation is insufficient and (in some systems that are designed to export) to inject excess PV generation back to the grid. This arrangement is highly reliable because the grid essentially provides an unlimited backup, but in itself does not help decrease grid dependency at times of low irradiance, unless it is coupled with local storage. Standalone (off-grid) systems are based solely on PV production with a stationary battery buffer, and are therefore appealing in remote settings where no grid connection is available, but both the size of the PV array and the size of the storage capacity need to be carefully considered to ensure reliability in meeting the charging needs during variable weather patterns and seasons. Hybrid systems integrate grid connection, PV generation, and stationary storage, providing the highest flexibility of operation: PV generation is given preference to satisfy the charging demand when possible, short-term fluctuations in irradiance are evened out by the battery buffer that is able to transfer solar energy to evening charging times, and the grid connection acts as a back-up in case of extended periods of low generation or during times of unusual high demand.

### *4.2 Maximum Power Point Tracking (MPPT)*

Since the power output of a PV array is nonlinearly dependent on the irradiance, temperature, and partial shading, a dedicated MPPT controller is needed to continually adjust the operating point of the PV array - usually via a DC-DC converter - to achieve the maximum available power at any given time. The most commonly used MPPT methods are the Perturb-and-Observe (P&O) and Incremental Conductance algorithms, which are simple and have low computation costs, but adjust the operating voltage of the array through a series of experiments, and monitor the change in power output. But these classical techniques may not perform well when the irradiance varies rapidly or when the samples are subject to partial-shading effects, and the powervoltage characteristic has more than one local maximum. To overcome this, metaheuristic and intelligent MPPT methods such as particle swarm optimization, grey wolf optimization, fuzzy-logic control and neural-network-based or adaptive-neuro-fuzzy-inference-system (ANFIS)-based controllers have been proposed which have shown better tracking speed and accuracy in the dynamic and partially shaded conditions in numerous simulation and experimental experiments.

### *4.3. Power-Electronic Architecture and DC-Bus Integration.*

Figure 1 illustrates a typical solar-integrated EV charging station design, which connects the PV array to a shared DC bus via an MPPT-controlled DC-DC converter, the utility grid to the shared DC bus via a bidirectional AC-DC converter, and the EV battery to the DC bus via a second DC-DC converter controlled by the vehicle onboard BMS. This DC bus is controlled by an energy management controller which makes decisions on a real time basis on how to use the available PV, grid and stored energy to satisfy the EV charging demand without exceeding the charging-rate limits and safety constraints reported by the connected vehicle BMS. A number of published designs also have a stationary battery bank option, also connected to the DC bus, that acts to smooth out short term variations in the sun, and to allow energy to be time-shifted, storing any surplus midday solar generation to be used at evening charging peaks when the sun has gone down.

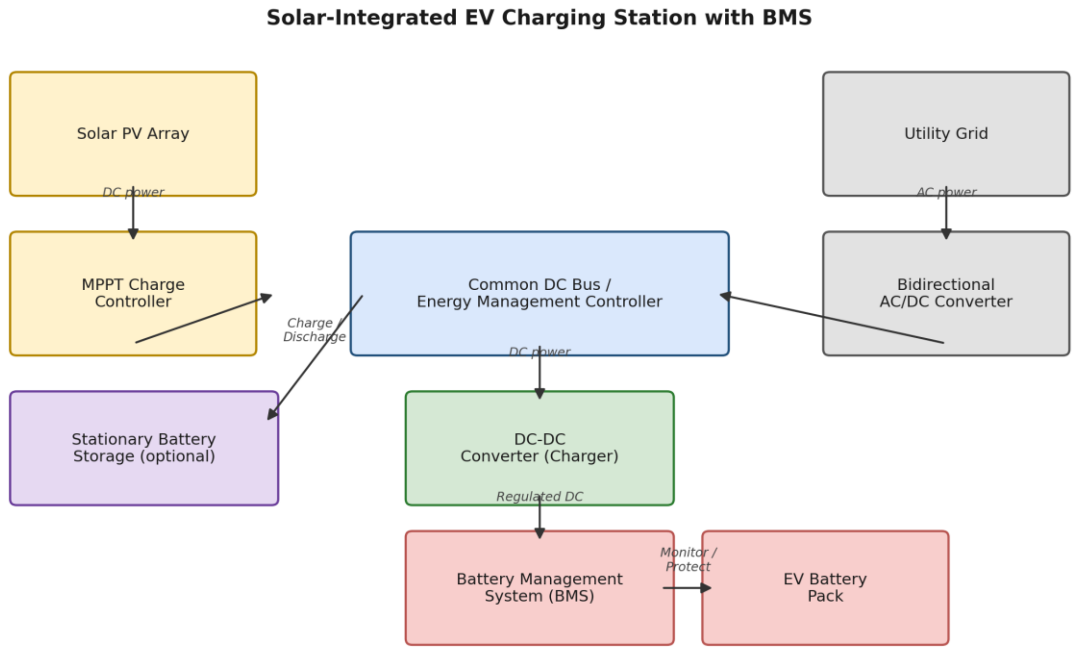


**Figure 1. Representative block-diagram architecture of a solar-integrated EV charging station with a common DC bus, MPPT-controlled PV interface, bidirectional grid converter, and BMS-coordinated EV charging path.**

### *4.4 Energy Storage Buffering*

The use of stationary battery storage has a unique purpose compared to the traction battery of the EV in solar-integrated charging stations. Through absorbing excessive PV generation during low chargin demand periods and discharging during high demand periods, stationary storage separates the time of solar generation and the time of EV charging demand which rarely happen at exactly the same time - solar generation is most often peaked in the midday, and charging demand often peaked in the early morning or evening at many locations. Second-life EV batteries that have remaining capacity to serve a stationary purpose once they can no longer serve in vehicles due to aging have been suggested and tried in a buffering application of this exact purpose, as a potential circular-economy solution that can increase the lifespan of EV battery packs before end-of-use recycling.

## 5. Solar-EV-BMS Systems Design and energy management.

### *5.1 System-Level Design Considerations*

An integrated solar-EV charging system with battery management will have to be co-optimized: the PV array needs to be sized against anticipated charging demand and local irradiance patterns; the stationary storage buffer needs to be sized to fill the gap between the solar availability and charging demand and be economically justified; the power-electronic converters should be rated to the peak power flows during the worst-case simultaneous charging conditions; and the energy management controller must be capable of communicating with and respecting the constraints reported by the onboard BMS of each connected vehicle, including maximum charge-acceptance rate, current SOC, and thermal limits. Due to the change in these limitations per vehicle and dynamism as the charging advances, the energy management controller needs to be a real-time optimization layer instead of a fixed allocation scheme.

### *5.2 Energy Management Strategies*

Solar-integrated EV charging energy management approaches are at one end of the spectrum with basic rule-based logic and at the other end highly optimizing and learning-based control. Rule-based strategies use a fixed priority sequence, such as direct PV-to-EV power transfer, followed by PV-to-storage charging, followed by grid import only as a last resort and are appealing because of their transparency and simplicity to implement, but are not necessarily cost- or efficiency-optimal in all circumstances. Alternative methods, model predictive control (MPC), constrain energy allocation as a repeated receding time optimization problem which uses time horizon predictions of solar irradiance, electricity price, and anticipated vehicle arrival and departure times to plan charging in such a manner as to minimize cost or maximize self-consumption of solar energy, within the operating constraints of each linked BMS. More recently, reinforcement-based energy management based on reinforcement-learning has been investigated as an alternative to adjusting scheduling policies to site-specific demand and generation characteristics without the need to have an explicit forecasting model, but instead learning through the operation experience. Figure 2 shows, at a representative location, the dislocation between a typical daily solar generation pattern and typical EV charging load which is the dislocation that stationary storage buffering and demand-responsive scheduling aim to resolve.

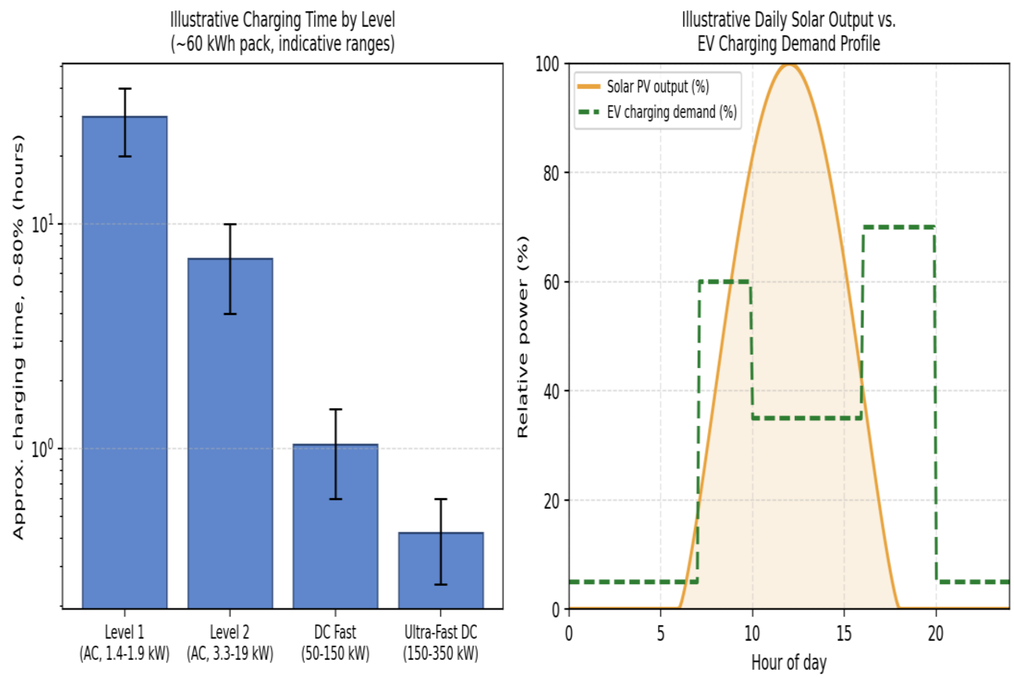


**Figure 2. Left: illustrative charging-time ranges across charging levels for an approximately 60 kWh battery pack (log scale; ranges compiled from published technical literature). Right: illustrative daily solar PV output profile compared with a typical EV charging demand profile, showing the temporal mismatch that motivates storage buffering and demand-responsive energy management.**

## *5.3 Pilot Implementations and Case Studies.*

Various published pilot and simulation studies are used to demonstrate various points along this design spectrum. Grids tied designs with a boost-converter MPPT stage to a shared DC bus with a bidirectional inverter to interact with the grid have been shown at power levels as low as a few kilowatts in single-vehicle residential or small commercial systems and multi-hundred-kilowatt PV arrays with multi-port converters capable of fast-charging at the highway-corridor scale. Off-grid solar EV chargers have been suggested and studied in areas where grid extension is not viable or costly, and typically couple a moderately sized solar array with a battery bank large enough to last through multiple consecutive periods of low irradiance, but are generally limited to slower Level 1- or Level 2-equivalent charging rates because of the practicality limits of standalone PV and battery bank size. Hybrid architectures with a fuel cell, supercapacitor or other storage with the PV array have also been investigated as a way of enhancing reliability and transient response especially in locations where the charging demand is highly variable. In all these studies, one commonality is that intelligent MPPT control (i.e. with fuzzy-logic, neural-network or metaheuristic-optimization-based controllers) is always found to be superior to classical Perturb-and-Observe tracking (under partial-shading and rapidly varying irradiance conditions) which directly translates into an increase in effective use of the solar power and a decrease in grid energy purchases at the station.

## *5.4 Economics and Environmental.*

Solar-integrated EV charging is economically dependent on both capital costs (PV modules, power electronics, stationary storage and grid interconnection equipment), operating costs (grid electricity purchases, maintenance, and battery replacement or degradation cost) and revenue or savings mechanisms (avoided grid purchases, demand-charge reduction, and, where available, export compensation or grid-service payments to participate in V2G). Due to the significant reduction in the price of PV modules and battery storage over the last 10 years, the levelized cost of charging energy produced by solar in most areas has become more competitive than grid electricity, especially where the solar irradiance is high and daytime charging is a significant use, like in a workplace charging lot. Environmentally, solar integration would make EV charging have a lower marginal carbon intensity compared to grid electricity produced by a fossil-heavy generation mix, and life-cycle analysis of second-life battery storage indicates more environmental benefits through delaying the resource-intensive recycling or disposal of used EV battery packs. Concurrently, the environmental argument in support of solar-integrated charging is site-specific, such as the intensity of carbon in the local grid, the manufacturing footprint of the PV panels, and ultimate end-of-life treatment of the panels, as well as the stationary storage batteries, highlighting the need to consider the full life-cycle analysis, and not the comparisons of operational phases alone.

## 6. Problems and Unresolved questions.

Although massive gains have been achieved in all three areas mentioned above, there are still some issues that restrict the performance, economics, and scalability of the solar-integrated EV charging system with battery management.

- Fast charging and battery degradation: Fast charging increases the rate of lithium plating, electrode stress and thermal cycling which generates an inherent trade-off between charging rate and the overall long-term health of the battery that BMS charging-control algorithms must continually manage.
- Solar intermittency and predictability: PV systems can change depending on weather conditions, the seasons of the year, and the time of day, making it more difficult to size storage buffers and predict the reliability of schedules of energy management, especially with no grid backup.
- Grid integration and power-quality effects: Groups of DC fast chargers, particularly when coupled to variable PV generation and bi-directional power exchange, may inject voltage swings, harmonic distortion, and focal transformer loading which should be carefully filtered by power-electronics and be compliant with grid-code requirements.
- Standardization gaps: 2 Standard connector standards (CCS, CHAdeMO, GB/T, NACS) and constantly changing communication protocols continue to create interoperability issues, and make the introduction of a universal, vendor-neutral energy management system difficult, in charge-point operators.
- SOC/SOH estimation error in the real world: Model-based and data-driven estimation algorithms that are accurate in a controlled laboratory or simulation environment may experience decreased accuracy when subjected to real-world driving conditions, temperature limits and aging, and this is why ongoing work on adaptive and self-learning estimation is sought.
- Economic feasibility of stationary storage buffering: Stationary storage enhances solar self-consumption and demand-shifting capability, but the cost of batteries and their degradation and losses in round-trip efficiency must be considered against the value of shifted energy, especially when second-life battery applications are involved where the useful life is more difficult to predict.
- Site planning and permitting: Co-locating PV arrays, stationary storage, and high-power DC charging equipment needs sufficient land or rooftop space, structural and electrical permitting, and may involve utility interconnection studies, which can significantly lengthen the project schedule compared to underlying equipment procurement and installation schedule.
- Cybersecurity and data privacy: With the introduction of charging stations as networked devices communicating with vehicles, the management systems, and the grid through protocols like ISO 15118 and OCPP, a bigger attack surface will exist, which needs to be secured against unauthorized access, manipulation of the data, and interference with the charging process or grid-support services.

## 7. Future Trends and Research Directions.

A number of new avenues of research will probably define the future of solar-integrated EV charging and battery management systems.

- Vehicle-to-grid and vehicle-to-everything (V2G/V2X) integration: Bidirectional charging systems that enable EVs to release stored energy back to the grid or a home at peak demand times are currently leaving pilot projects and entering into more general commercial applications with consequences to the BMS design, battery degradation modeling, and energy management optimization.
- AI-based energy management and predictive maintenance: Machine-learning models find more and more applications in not just SOC/SOH estimation, but also demand prediction, adaptive MPPT control, and predictive fault detection throughout the charging station and battery pack, with a trend toward digital-twin models that reflect the physical system in real time.
- Second-life battery storage Research into solar-integrated charging station stationary storage buffers using retired EV battery packs as second-life storage buffers is potentially a cost-effective and circular-economy-compatible storage route, but further development of rapid and inexpensive SOH assessment of heterogeneous retired packs is required.
- Ultra-fast and megawatt-scale charging: Further scaling of the Megawatt Charging System and associated high-power architectures of heavy-duty vehicles will necessitate associated improvements in thermal management, cell chemistry tolerance to high charging rates, and grid-interconnection design.
- Wireless and dynamic charging: Static wireless charging pads are being transitioned to commercial offering to passengers and transit vehicles, and dynamic (in-motion) wireless charging integrated into the road infrastructure is still just an active but more recent field of research with implications to continuous, lower-peak-power BMS operation.
- Solid-state and next-generation battery chemistries: The ongoing research in solid-state and lithium-sulfur, and other next-generation battery chemistries will be more energy-dense and offer higher safety margins, which, in turn, will redefine the BMS thermal management and SOC/SOH estimation requirements.
- Standardized, interoperable smart-charging ecosystem: Integration Convergence to common connector and communication standards and open, interoperable energy management platforms would simplify integration of solar-EV charging systems, and would enable aggregation of distributed charging stations into grid-support resources.

## 8. Conclusion

The network of electric vehicle charging, battery control, and solar photovoltaic integration are highly interrelated technical areas the maturation of which will define the pace and sustainability of the electrification of road transport. This review has followed the history of the development of charging infrastructure, starting with the basic Level 1 AC charger, then DC fast charging with megawatt scale, the fundamental capabilities of battery management systems such as SOC/SOH estimation, cell balancing and thermal management, and the architectures and control strategies to integrate solar generation with EV charging stations. The literature review indicates that intelligently designed, solar-integrated charging stations, constructed around a shared DC bus, state-of-the-art MPPT control, suitably sized storage buffering, and an energy management controller mindful of the constraints as reported in BMS have a viable roadmap to lower-cost, lower-carbon EV charging. To achieve this potential at scale, it will be necessary to make further advances in battery degradation-conscious fast charging, robust SOC/SOH estimation in the real world, connector and communication protocol standardization, and affordable storage and V2G planning, as well as to consider grid integration and cybersecurity as charging networks become more interconnected and data-driven.

### References

1. Acharige, S. S. G., Le, A. T., Yan, K., et al. (2023). Review of electric vehicle charging technologies, standards, architectures, and converter configurations. IEEE Access, 11, 41218-41255. https://doi.org/10.1109/ACCESS.2023.3267164
2. Omase, N., Mittal, S. K., Palaniraja, S., Guchhait, P., & Patil, M. (2023). A comprehensive review of electric vehicle charging infrastructure and associated challenges. International Journal of Science and Research Archive, 10(1), 834-840. https://doi.org/10.30574/ijsra.2023.10.1.0832
3. International Energy Agency (IEA). (2023). Trends in charging infrastructure - Global EV Outlook 2023. IEA, Paris.
4. Sithara S. G. Acharige et al. and related contributions on standardization; see also: Regulations and standards for electric vehicle charging infrastructure: a comparative analysis. Sustainable Energy Technologies and Assessments, 73 (2025), Article 104119.
5. Rahman, M. A., et al. (2017). A review of lithium-ion battery state of charge estimation and management system in electric vehicle applications: Challenges and recommendations. Renewable and Sustainable Energy Reviews.

6. Gaga, A., Tannouche, A., Mehdaoui, Y., & El Hadadi, B. (2022). Methods for estimating lithium-ion battery state of charge for use in electric vehicles: a review. Energy Harvesting and Systems, 9(2), 211-225. https://doi.org/10.1515/ehs-2021-0039
7. A comprehensive review of state of charge estimation in lithium-ion batteries used in electric vehicles. (2023). Journal of Energy Storage / ScienceDirect.
8. A review on state of charge estimation methods for lithium-ion batteries based on data-driven and model fusion. (2025). Journal of Energy Storage.
9. Review of battery state estimation methods for electric vehicles - Part I: SOC estimation. (2024). Journal of Energy Storage.
10. Comprehensive review of battery management systems for electric vehicles: Thermal management, charging strategies, and emerging technologies. (2025). Journal of Power Sources.
11. Review of Cell-Balancing Schemes for Electric Vehicle Battery Management Systems. (2024). Energies, 17(6), 1271. https://doi.org/10.3390/en17061271
12. A Comprehensive Review of the Art of Cell Balancing Techniques and Trade-Offs in Battery Management Systems. (2025). Energies, 18(13), 3321. https://doi.org/10.3390/en18133321
13. A critical review of battery cell balancing techniques, optimal design, converter topologies, and performance evaluation for optimizing storage system in electric vehicles. (2024). Journal of Energy Storage.
14. Murugan, M., et al. (2025). A Comprehensive Review of Thermal Management Methods and Ideal System Design for Improved Electric Vehicle Battery Pack Performance and Safety. Energy Science & Engineering. https://doi.org/10.1002/ese3.2081
15. A grid tied solar photovoltaic based off board electric vehicle charger in G2V and V2G mode. (2024). AIP Advances, 14(9), 095203.
16. Design and Performance Analysis of a Grid-Integrated Solar PV-Based Bidirectional Off-Board EV Fast-Charging System Using MPPT Algorithm. (2026). Energies, 19(7), 1656. https://doi.org/10.3390/en19071656
17. Solar powered electric vehicle charging system: a comprehensive review. (2025). Discover Electronics. Springer Nature.
18. An integrative review of standalone solar powered EV charging stations: Standards, policies, design aspects, and future directions. (2025). Sustainable Energy Technologies and Assessments.
19. A grid-integrated PV-powered EV charging station featuring artificial neural network-based MPPT and comprehensive power flow control. (2025). E3S Web of Conferences.
20. Design and simulation of 4 kW solar power-based hybrid EV charging station. (2024). Scientific Reports, 14. https://doi.org/10.1038/s41598-024-56833-5
21. A novel and sturdy MPPT architecture for grid-tied EV charging stations using Ali Baba and forty thieves optimization. (2025). Discover Sustainability. Springer Nature.
22. A robust MPPT framework based on GWO-ANFIS controller for grid-tied EV charging stations. (2024). Scientific Reports, 14; also PMC11680877.
23. Grid tied hybrid PV fuel cell system with energy storage and ANFIS based MPPT for smart EV charging. (2025). Scientific Reports.