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# Asset Optimization and Value Enhancement of EV Charging Infrastructure under Aggregated Operation Models: Methods, Frameworks, and Practices

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**Abstract:** The rapid growth of electric vehicles (EVs) has significantly increased the demand for efficient and profitable charging infrastructure. Traditional station-level deployment often suffers from low utilization and delayed return on investment. Aggregated operation models-integrating multi-station, multi-brand, and multi-operator networks-offer new pathways for asset optimization, cost reduction, and value enhancement. This review systematically examines the methods, frameworks, and practices of aggregated EV charging networks. Key aspects include demand and load forecasting, infrastructure capacity planning, intelligent operational control, and digital twin-based simulations. The study further explores mechanisms for CAPEX and OPEX optimization, multi-stream revenue generation, grid integration, and flexibility services such as V1G/V2G participation. Global case studies illustrate successful implementations, while challenges such as interoperability, real-time dispatch scalability, and data security are discussed. Finally, future directions including AI-driven optimization, ultra-large-scale aggregation, and cross-energy-system coordination are proposed, highlighting the strategic potential of aggregation in sustainable EV infrastructure development.

**Keywords:** EV charging; aggregated operation; asset optimization; V2G; grid flexibility; multi-stream revenue

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## 1. Introduction

### *1.1. Growth of Electric Vehicles and Emerging Challenges in Charging Infrastructure*

The rapid global adoption of electric vehicles (EVs) has driven an unprecedented demand for charging infrastructure over the past decade. According to projections from multiple energy agencies and industry reports, the global EV stock is expected to exceed 250 million units by 2030, representing several-fold growth relative to 2020 levels. This accelerated expansion places strong pressure on charging networks, requiring fast, reliable, and widely accessible charging services to sustain EV adoption. However, despite substantial capital investment in public and semi-public charging stations, the economic performance of these assets remains far from satisfactory. A considerable proportion of charging infrastructure operates at low utilization rates—often below 10–15% in many cities—leading to long payback periods and discouraging private investment [1].

Underlying this problem is the inherently uneven spatiotemporal distribution of charging demand. Peak periods are highly concentrated, while off-peak hours exhibit significant idle capacity. Furthermore, charging behavior depends on location, vehicle type, electricity pricing, driver routines, and the availability of alternative charging options such as home charging. These factors contribute to mismatches between planned capacity and actual usage. As a result, many charging stations, particularly fast-charging hubs with high power ratings, face underutilization while incurring substantial operational and depreciation costs. The discrepancy between infrastructure deployment and optimal asset performance has become a critical bottleneck that threatens the financial sustainability of the charging ecosystem.

Compounding the challenge, traditional station-level business models tend to operate in organizational silos. Different brands, operators, and networks manage their assets independently, leading to fragmented service systems, duplicated investments, incompatibility between platforms, and inefficiencies in operational decision-making. This fragmentation restricts the possibility of coordinated load balancing, aggregated value creation, and demand-supply matching across infrastructures, making it difficult for individual stations to achieve economies of scale or to participate effectively in energy and flexibility markets. As the EV industry matures, overcoming these structural inefficiencies has become essential for improving asset value and accelerating charging network deployment [2].

### *1.2. Why Aggregated Operation Models Can Enhance Asset Value*

Aggregated operation models-defined as multi-station, multi-brand, and multi-operator coordination frameworks-have emerged as a promising solution to the limitations of traditional standalone charging operations. Under such models, multiple charging stations are digitally interconnected through a unified platform that enables shared resource scheduling, coordinated load management, and collective optimization. By pooling assets and operational data, aggregated operators can dynamically allocate power capacity, redistribute charging demand among stations, and reduce idle time across the network. This multi-station coordination effectively smooths peaks and fills valleys, thereby increasing the overall utilization rate of the infrastructure cluster.

Another key advantage lies in interoperability. Aggregated operation frameworks facilitate the integration of heterogeneous hardware-different charger brands, standards, and communication protocols-through unified access layers and standardized interfaces. The ability to integrate multi-brand chargers into a single management platform not only reduces fragmentation but also creates platform-level economies of scale. This interoperability also enhances user experience by enabling unified payment, access, and pricing mechanisms, which can attract more users and stabilize service demand across the network [3].

Furthermore, aggregated operators are able to unlock new forms of value that are inaccessible to individual stations. By managing a large fleet of coordinated chargers, aggregated networks can behave as large-scale controllable loads or even virtual power plants (VPPs) in power systems. This enables participation in demand response programs, frequency regulation markets, and distributed energy resource (DER) integration-providing additional revenue streams beyond conventional charging service fees. When combined with vehicle-to-grid (V2G) technologies, energy storage systems, or renewable generation, aggregated operators can execute energy arbitrage, optimize electricity procurement, or supply grid-supportive services. Theseadvanced value mechanisms significantly improve the return on investment (ROI) and operational resilience of charging infrastructure assets [4].

### *1.3. Objectives and Contributions of This Review*

Given the growing interest in aggregated operation models and their transformative potential, there remains a need for a systematic review that consolidates methods, models, frameworks, and best practices in this emerging field. Existing studies mainly focus on isolated aspects such as load forecasting, charging station planning, or V2G control, but comprehensive insights into how these components interact within aggregated operation architectures are still limited. As charging infrastructures evolve into large-scale, data-driven, and grid-interactive assets, the industry requires a structured understanding of the technological, economic, and regulatory dimensions that shape asset optimization and value enhancement.

This review aims to fill this gap by providing an integrated examination of aggregated operation models for EV charging infrastructure. The first contribution of this study is to synthesize the conceptual foundations of aggregated operation-including system architectures, functional components, and interoperability mechanisms. The second contribution is to classify and evaluate asset optimization methods relevant to aggregated charging networks, covering demand forecasting, capacity planning, scheduling, pricing, digital twin modeling, and operational control. The third contribution is to analyze value enhancement pathways enabled by aggregation, including CAPEX/OPEX reduction, multi-stream revenue mechanisms, and participation in flexibility and ancillary-service markets [5].

Finally, this review incorporates real-world case studies from China, Europe, and the United States to demonstrate how aggregated models are being deployed in practice, and it highlights existing challenges, regulatory considerations, and future research opportunities. By presenting a holistic framework, this review aims to support researchers, policymakers, and industry practitioners in understanding how aggregated operation models can significantly improve the efficiency, sustainability, and financial viability of EV charging infrastructure.

## 2. Aggregated Operation Models and System Architecture

### *2.1. Aggregated Operation: Concepts and Types*

Aggregated operation refers to the coordinated management of multiple charging stations, charger brands, operators, and power resources through an integrated platform that optimizes the charging service network as a unified system. This model moves beyond the limitations of standalone station operation by enabling cross-station coordination, power sharing, and large-scale load control. Several representative forms of aggregation have emerged, each offering different capabilities and value enhancement mechanisms [6].

The Multi-Operator Aggregator (MOA) is one of the most widely discussed models. MOAs integrate chargers from different operators and brands into a unified operational environment, enabling interoperability, unified billing, and shared scheduling. Through such multi-operator coordination, MOAs reduce system fragmentation and support economies of scale. A related model is the Virtual Charging Network (VCN), which connects geographically dispersed charging stations into a single virtualized network. In a VCN, power resources, charging slots, and user demand are managed collectively, allowing the operator to optimize utilization across the entire network rather than at individual sites.

Another important category is the V2G Aggregation Model, which focuses on coordinating the bidirectional charging capabilities of EVs. When aggregated at scale, V2G-enabled chargers function as distributed energy assets capable of providing ancillary services such as frequency regulation, spinning reserve, and peak shaving. Finally, the Grid-Interactive EV Charging Operator integrates aggregated charging networks directly with the electricity grid. This model emphasizes real-time grid coordination, enabling demand response, renewable energy integration, and dynamic power allocation across stations. Together, these models illustrate the multi-layered nature of aggregated operation and its potential to transform charging infrastructure into a flexible, grid-responsive asset class [7].

### *2.2. Functional Architecture*

The functional architecture of aggregated operation models is built on several key components that together enable efficient system-wide optimization. First, unified scheduling and power sharing constitute the core operational mechanism. Through centralized or distributed control algorithms, the platform can dynamically allocate charging power across stations, balance load peaks, and minimize idle capacity. This approach significantly improves the stability of the operator's power footprint and enhances the effective utilization of installed capacity.

Second, interoperability is essential. Aggregated systems require seamless integration of multi-brand chargers and heterogeneous hardware through standardized communication protocols and interface layers. Automated onboarding mechanisms allow chargers from different vendors or networks to join the aggregated platform with minimal configuration, thereby reducing the costs associated with system integration and maintenance. Interoperability also enhances user experience by enabling unified access, authentication, and payment across all stations within the aggregated network [8].

Third, aggregated operators rely on user and load aggregation models to optimize service supply. By analyzing behavioral patterns, mobility data, fleet schedules, and historical usage, the platform can forecast demand at both the individual-station and network-wide levels. These predictive insights enable more effective charging slot allocation, queue management, and congestion mitigation. Finally, the architecture includes a robust data platform that supports forecasting, billing, asset monitoring, and resource pooling. Data-driven analytics form the backbone of aggregated operation, enabling real-time status tracking, predictive maintenance, and monetization through grid services or energy markets [9].

Given the complexity and multi-dimensional nature of aggregated operation, a structured comparison with traditional station-level operation is necessary to highlight the advantages of the aggregated model. Table 1 provides a comparative overview across several key dimensions, including cost structure, utilization improvement potential, scheduling flexibility, revenue opportunities, and technical requirements.

**Table 1.** Comparison of Traditional vs. Aggregated Operation Models.

| Dimension | Traditional Station-Level Operation | Aggregated Operation Model |
|---|---|---|
| Cost Structure | High CAPEX per station; duplicated infrastructure and backend systems | Shared CAPEX/OPEX; economies of scale through centralized systems |
| Utilization Improvement Potential | Low; demand fluctuations cannot be absorbed | High; demand smoothing and cross-station load balancing |
| Scheduling Flexibility | Limited to local station constraints | Network-wide scheduling and power sharing |
| Revenue Potential | Mainly charging service fees | Multi-stream: DR programs, ancillary services, V2G, data services |
| Technical Requirements | Basic station management | Interoperability protocols, real-time data, coordinated control algorithms |

### *2.3. Comparison with Traditional Station-Level Operation*

Traditional charging operations are constrained by the physical and organizational boundaries of individual stations. Each station must manage its own power allocation, pricing, user flow, and maintenance activities, which results in duplicated investment and inefficiencies in both cost and operation. Station utilization also varies widely depending on location, time of day, and user behavior, making it difficult for single-station operators to achieve stable revenue or optimal asset performance [10].

Aggregated operation fundamentally alters this paradigm by integrating multiple stations into a shared, coordinated environment. Operators can dynamically redistribute demand, optimize power across the network, and reduce idle time while avoiding local overloads. The aggregated model also unlocks participation in grid services and flexibility markets, which would be impossible for isolated stations due to their limited scale. Furthermore, the integration of multi-brand chargers and unified data services enhances user experience and operational transparency.

In summary, aggregated operation introduces systemic improvements across utilization, cost efficiency, revenue diversity, and grid interoperability. It represents a shift from isolated infrastructure assets toward a coordinated, scalable, and digitally intelligent charging ecosystem [11].

## 3. Methods for Asset Optimization

### *3.1. Demand and Load Forecasting Methods*

Accurate demand and load forecasting form the foundation of asset optimization in aggregated charging networks. Because charging demand exhibits high spatial-temporal variability, forecasting methods must capture both short-term operational dynamics and longer-term expansion needs. Traditional time-series models such as ARIMA, exponential smoothing, and state-space models remain widely used due to their interpretability and low computational burden. However, with the increasing granularity of charging data, machine learning algorithms-including random forests, gradient boosting regression, and support vector regression-provide improved capability to capture nonlinear demand patterns [12].

The adoption of deep learning further enhances forecasting accuracy. Long Short-Term Memory (LSTM) networks, temporal convolutional networks (TCN), and hybrid attention-based architectures can model complex dependencies, seasonal patterns, and abrupt fluctuations in charger utilization. These models are especially valuable for high-resolution forecasting required in real-time scheduling or V2G coordination. For aggregated networks, deep learning enables multi-station forecasting by considering inter-station correlations and shared mobility patterns.

User behavior prediction also plays a crucial role. Factors such as trip purpose, vehicle type, availability of home charging, and mobility habits influence both charging frequency and power demand. Integrating geospatial and traffic data-such as road flows, land-use features, and proximity to commercial centers-improves spatial prediction accuracy. For fleet-dominated regions, schedules and routing data of taxis, ride-hailing vehicles, and logistics fleets can significantly enhance load predictability.

Multi-station joint load forecasting is essential in aggregated operation models. By analyzing correlations across stations within the network, operators can anticipate congestion, identify underutilized assets, and optimize power allocation. Joint forecasting supports higher-level decisions such as cross-station routing, shared capacity management, and network-wide peak shaving. Overall, forecasting models serve as the backbone of asset optimization, enabling data-driven decisions across planning, scheduling, pricing, and grid interaction [13].

### *3.2. Infrastructure and Capacity Optimization*

Infrastructure and capacity optimization directly influence the long-term economic viability of charging assets. Integrated siting-capacity models combine spatial analysis, mobility demand estimation, and grid constraints to determine optimal locations and power configurations. These models typically employ mixed-integer linear programming (MILP) or metaheuristic algorithms to balance installation cost, expected utilization, and service coverage. In aggregated operation, siting decisions can be coordinated across stations to avoid redundant investments and maximize coverage efficiency.

Shared capacity is one of the defining advantages of aggregated networks. Instead of allocating fixed power to each station, operators can pool transformer capacity or upstream grid connections and distribute power dynamically based on real-time demand. Shared capacity reduces both CAPEX and OPEX by minimizing overprovisioning and improving transformer utilization. This concept extends to distributed energy resources (DERs) such as photovoltaics and energy storage systems, which can be managed collectively to supply charging demand or provide grid services.

Optimizing station configurations also enhances asset performance. The mix of DC fast chargers (DCFC), AC chargers, and V2G-enabled chargers must align with user behavior, grid constraints, and revenue opportunities. For example, stations near highways may emphasize high-power DCFCs, while urban destinations may prioritize AC chargers with moderate power ratings. Aggregated operation allows planners to consider such configurations at the network level, treating charger types as a portfolio rather than isolated assets. Including V2G functionality further enables flexibility services, energy arbitrage, and grid support, increasing the long-term value of the infrastructure.

### *3.3. Operational Optimization and Control*

Operational optimization ensures that charging assets perform efficiently on a day-to-day basis. Intelligent scheduling lies at the heart of this process. Load shifting strategies schedule charging during low-price or low-demand periods, while peak shaving reduces demand during system peaks to avoid excessive tariffs or local overloads. Aggregated networks can coordinate these strategies across stations, maximizing network-wide efficiency and mitigating congestion at high-demand locations.

Dynamic queue management and resource sharing improve user experience and asset utilization. Instead of treating each station as an isolated service node, aggregated operators can implement network-wide queue allocation. Users may be redirected to nearby stations with lower waiting times, or charging loads can be redistributed based on predicted congestion. This cross-station coordination significantly reduces average queue length and improves service availability.

Real-time pricing is another powerful control mechanism. By dynamically adjusting service fees based on demand, grid conditions, or operational objectives, operators can influence user behavior to achieve better load distribution. Time-sensitive and congestion-based pricing models are increasingly used to spread demand across stations and time slots. Aggregated networks can also utilize traffic redirection strategies, where users are incentivized or automatically guided to alternative stations when local demand exceeds operational thresholds.

Together, these operational optimization strategies transform charging networks from static infrastructure into intelligent, responsive systems capable of balancing user needs, grid constraints, and financial objectives.

### *3.4. Digital Twin and Simulation*

Digital twin modeling has emerged as a critical tool for simulating and optimizing aggregated charging networks. A digital twin represents a virtual counterpart of the physical charging infrastructure, enabling operators to test scheduling strategies, evaluate expansion plans, and simulate demand scenarios without disrupting real-world operations. By integrating real-time data streams, digital twins can continuously update system states and provide actionable insights for operational and planning decisions.

Virtual network simulations allow operators to assess station utilization under different demand distributions, pricing schemes, or charger configurations. These simulations can incorporate renewable energy profiles, storage behavior, and grid constraints to evaluate complex interactions. Queueing simulations, including M/M/1, M/G/c, or networked queueing systems, help operators estimate waiting times, service rates, and congestion probabilities across the aggregated network. Such insights guide decisions on charger deployment, queue management strategies, and optimal resource allocation.

Monte-Carlo simulations further enhance planning under uncertainty by evaluating thousands of scenarios involving stochastic demand, equipment failures, user behavior variability, or renewable fluctuations. These simulation approaches support risk-aware decision-making and ensure robust performance of aggregated assets under diverse conditions.

Given the breadth of methods involved, Table 2 summarizes the major optimization approaches, their target scenarios, algorithm types, optimization goals, and technical requirements.

**Table 2.** Optimization Methods and Objectives.

| Scenario | Algorithm Type | Optimization Goals | Technical Requirements |
|---|---|---|---|
| Demand & Load Forecasting | Time-series models, ML, deep learning | Improve accuracy, reduce forecasting error | High-quality historical data, sensor integration |
| Siting & Capacity Optimization | MILP, heuristics, metaheuristics | Minimize CAPEX/OPEX, maximize coverage | GIS data, grid constraints, mobility datasets |
| Network-wide Scheduling | Linear programming, model predictive control | Load shifting, peak shaving | Real-time data, coordinated control systems |
| Queue & Resource Management | Queueing theory, reinforcement learning | Reduce waiting time, balance station load | Cross-station connectivity, predictive analytics |
| V2G & DER Optimization | Bi-directional control, stochastic optimization | Maximize flexibility revenue, enhance grid stability | V2G hardware, market access, real-time metering |
| Simulation & Digital Twins | Monte-Carlo, discrete-event simulation | Evaluate strategies, assess uncertainty | High-performance computing, dynamic data feeds |

## 4. Value Enhancement Mechanisms under the Aggregated Model

Aggregated operation models reshape how charging infrastructure creates value by shifting optimization from the level of individual stations to the level of multi-station clusters or virtual networks. Instead of managing each site as an isolated asset with its own investment, operating processes, and revenue path, aggregation enables the coordinated deployment of capital, unified operations, and diversified monetization strategies. This section reviews three major mechanisms through which aggregated EV-charging operators enhance asset value: CAPEX optimization, OPEX reduction, and the creation of multi-stream revenue models.

### *4.1. CAPEX Optimization*

A key source of value under aggregation comes from structurally reducing capital expenditure through shared infrastructure and system-level planning. In conventional station deployment, every site must independently obtain transformer capacity, grid connections, and power electronics. This leads to redundant capacity and underutilized investment, especially in regions where charging demand fluctuates across time and locations. Aggregated operators, in contrast, can deploy shared distribution capacity, allowing multiple stations to draw power from a pooled capacity resource. By coordinating capacity allocation through load forecasting and intelligent scheduling, the network reduces peak demand seen by the grid and lowers the required upstream connection capacity. This significantly decreases initial grid-connection costs.

CAPEX efficiency also benefits from cluster-level investment planning, where expansion decisions are informed by multi-station demand prediction, queueing simulation, and utilization data. Rather than making incremental investments at individual stations, aggregated operators can identify high-value nodes within the network and optimize capacity upgrades based on system-wide marginal benefits. This reduces the frequency of overbuilt or underutilized sites.

Finally, aggregation supports economies of scale through bulk procurement of charging hardware, unified backend systems, and shared O&M tools. When multi-brand chargers are integrated into a single interoperability layer, operators can standardize installation, software deployment, and maintenance procedures. Bulk purchasing reduces per-unit equipment cost, and shared diagnostic tools avoid repeated investment across stations. Together, these mechanisms lower the cost-per-kW of infrastructure deployment and accelerate payback periods.

### *4.2. OPEX Reduction*

Operational expenditure forms a substantial portion of lifetime charging costs, and aggregation offers multiple levers for reducing these expenses. The first is remote operations and maintenance, enabled by unified monitoring platforms that track charger status, communication health, safety alarms, and usage patterns across all connected stations. Centralized remote control allows operators to resolve a large portion of faults-such as firmware resets, communication restarts, or configuration updates-without on-site intervention, significantly reducing labor costs and travel time.

A second source of OPEX reduction comes from predictive maintenance, where multi-station data feeds machine-learning models that identify early signs of failure. Anomaly detection based on temperature, voltage, charger idle patterns, and historical fault logs enables proactive intervention before issues escalate into costly downtime. This not only reduces repair expenses but also improves charger availability, indirectly increasing user satisfaction and revenue.

Operational efficiency is further enhanced through data-driven dispatch optimization, such as balancing loads across stations, redirecting users from congested sites, or adjusting charging profiles to avoid demand charges. With aggregated data and network-wide visibility, operators can infer the best charging allocation strategy to minimize operational costs while maintaining user experience. Compared with station-level management, aggregation provides far greater flexibility for adjusting load profiles, reducing energy costs, and improving asset longevity.

### *4.3. Multi-Stream Revenue Models Enabled by Aggregation*

While cost reductions strengthen financial resilience, the most distinctive advantage of aggregated operation lies in its ability to create multiple revenue streams beyond traditional charging fees. Conventional station operators predominantly rely on service fees collected per kWh, but aggregated models allow for more sophisticated monetization.

First, aggregation enables network-wide charging service revenue complemented by membership programs that unify pricing, billing, and user experience across stations. A consistent and flexible membership system helps attract frequent users and enhances customer retention.

Second, aggregated operators gain the ability to implement dynamic pricing, adjusting tariffs based on time-of-use, real-time demand, or congestion levels. Such pricing strategies stabilize utilization across stations and maximize revenue during peak periods.

Third, aggregation allows operators to participate in grid-interactive value streams, including demand response and ancillary services. When a network of stations is treated as a controllable load resource, the aggregated operator can modulate charging power in exchange for compensation from grid operators. This flexibility is significantly amplified when V1G or V2G capabilities are integrated, enabling additional revenue through frequency regulation, peak shaving, or even energy discharge during high-price periods.

Fourth, aggregated networks facilitate spatiotemporal arbitrage, leveraging price differences across time and locations. By shifting load to low-price intervals or routing users to stations with favorable energy costs, operators capture revenue from energy market dynamics.

Finally, aggregated platforms produce large-scale operational and behavioral data that support monetization through predictive services, such as infrastructure planning insights, mobility pattern analytics, or third-party collaboration projects.

These diverse monetization channels are summarized in Table 3, which outlines the primary value streams, their revenue cycles, required technological capabilities, and implementation difficulty.

**Table 3.** Value Streams for Aggregated Charging Operators.

| Value Stream Category | Specific Revenue Items | Revenue Cycle | Required Technical Capability | Implementation Difficulty |
|---|---|---|---|---|
| Charging Services | kWh-based fees, membership programs | Short-term | Billing & CRM systems | Low |
| Dynamic Pricing | TOU pricing, congestion pricing | Short-term | Pricing algorithms, forecasting | Medium |
| Grid Services | Demand response, frequency regulation | Mid-term | Aggregation control, V2G/V1G | High |
| Energy Arbitrage | Temporal and spatial arbitrage | Mid-term | Optimization engine, market interface | High |
| Data-Driven Services | Predictive analytics, planning data | Long-term | Big-data platform | Medium |
| Shared O&M Benefits | Unified tools, remote O&M efficiency | Short-term | Centralized operations | Low |

## 5. Grid Integration and Flexibility Services

As EV adoption accelerates, the interaction between charging infrastructure and the power system becomes increasingly central to both grid stability and charging network profitability. Aggregated charging networks-characterized by multi-station coordination, unified load control, and integrated forecasting systems-offer significantly more flexibility than isolated stations. By functioning as controllable, dispatchable load resources, these networks enable enhanced participation in grid-support markets, improve hosting capacity at the distribution level, and support the integration of distributed energy resources (DERs). This section examines how aggregated EV charging can serve as a scalable flexibility asset, focusing on controllable load management, V1G/V2G applications, system stability, and the regulatory conditions under which these services can be deployed.

### *5.1. Aggregated EV Charging as a Flexible Load Resource*

Aggregated charging networks transform geographically dispersed stations into a unified flexible load portfolio. By consolidating real-time operational data across stations-such as occupancy levels, charger availability, and local grid constraints-operators can dynamically adjust charging power at the cluster level. This multi-station controllability allows aggregated operators to modulate the total charging load with far greater precision than single-station systems.

A key form of flexibility comes from load shifting, where aggregated networks reduce or defer non-urgent charging sessions to off-peak periods. When supported by user behavior prediction and multi-station load forecasting, the operator can coordinate charging schedules to avoid coincident peaks across the cluster. Quantitatively, this can produce substantial peak-load reductions; studies indicate that aggregated station clusters can achieve power reduction rates exceeding 20-40% during peak windows, depending on fleet composition and user flexibility. Such load reductions directly enhance grid hosting capacity and help distribution operators defer infrastructure upgrades.

Moreover, aggregated charging networks can provide upward and downward load modulation within seconds to minutes, supporting fast-acting grid-response services. Through unified dispatch, operators can combine flexible demand from multiple stations, making them viable participants in ancillary service markets traditionally dominated by large industrial loads.

### *5.2. V2G/V1G and Vehicle Fleets*

The flexibility potential expands further when aggregated operators integrate vehicle fleets-such as taxis, ride-hailing vehicles, logistics vans, and corporate EV fleets-into their portfolios. Unlike private EVs, fleet vehicles have predictable charging patterns and long dwell times, making them ideal controllable resources for both V1G (unidirectional) and V2G (bidirectional) operations.

With aggregation, fleets can collectively participate in frequency regulation, reserve capacity markets, and peak load reduction programs, providing services that require consistent and reliable response. For instance, a fleet of several thousand logistics vehicles, when coordinated through an aggregator, can deliver multi-megawatt regulation capacity. Because the aggregator can distribute response signals across multiple depots and stations, the reliability requirement for grid services is more easily satisfied.

V2G-capable fleets also enable energy export during high-price periods or grid contingencies. By discharging from vehicles with sufficient state-of-charge, aggregated operators can generate revenue while simultaneously supporting system stability. This capability becomes especially valuable in regions with high renewable penetration, where V2G can help absorb surplus solar generation during mid-day and deliver energy during evening peaks. Thus, aggregation significantly enhances the economic and operational feasibility of V2G/V1G services.

### *5.3. Power System Stability and Hosting Capacity*

Beyond market participation, aggregated charging networks directly influence the technical stability of local power systems. High-density charging deployments risk causing localized transformer overloads, feeder congestion, or voltage deviations. Through system-wide monitoring and coordinated scheduling, aggregated operators can limit simultaneous peak loads, preventing overloading of sensitive grid nodes.

Aggregated networks also interface naturally with distributed energy resources, particularly photovoltaic (PV) installations and energy storage systems (ESS). When integrated at the station cluster level, PV+ESS systems can supply local charging demand, smooth fluctuations, and provide fast-response support for both the charging network and the grid. The synergy between DERs and coordinated charging enhances distribution-level hosting capacity, reducing curtailment of renewable energy and enabling more efficient local energy balancing.

Furthermore, aggregated charging networks can support voltage regulation and reactive power management when chargers with advanced grid-support functionalities are deployed. Unified control strategies allow the operator to distribute these functions across the cluster, further improving system reliability.

### *5.4. Regulatory and Market Context*

The provision of flexibility services requires supportive regulatory frameworks, communication standards, and market-access mechanisms. At the technical level, protocols such as OCPP (Open Charge Point Protocol) and ISO 15118 form the foundation for interoperability and secure communication between chargers, vehicles, and aggregators. ISO 15118, in particular, provides essential capabilities for V2G operation, including secure authentication and real-time control.

On the market side, participation in demand response or ancillary service programs depends heavily on tariff structures, minimum resource size requirements, and market-entry rules established by grid operators. In some regions, aggregators must meet strict response accuracy standards to qualify for regulation markets, while in others, participation may be limited to licensed retailers or large industrial users. The effectiveness of aggregated flexibility services therefore hinges on clear market pathways, transparent compensation mechanisms, and regulatory recognition of EV aggregators as legitimate grid resources.

These various flexibility services are summarized in Table 4, which categorizes the primary grid-support functions available to aggregated charging networks.

**Table 4.** Flexibility Services Provided by Aggregated Charging Networks.

| Flexibility Service | Description | Technical Requirements | System-Level Impact | Implementation Difficulty |
|---|---|---|---|---|
| Frequency Regulation | Fast up/down response using V1G/V2G | Real-time control, ISO 15118 | Supports grid frequency stability | High |
| Reserve Capacity | Standby load reduction or discharge | Aggregation platform, fleet participation | Enhances system reliability | Medium-High |
| Demand Response | Load shifting, peak shaving | Forecasting, load control | Reduces peak demand & grid stress | Medium |
| V2G Energy Transactions | Vehicle-to-grid discharge | Bidirectional chargers, market interface | Provides energy during peak periods | High |
| Distribution-Level Optimization | Congestion mitigation, voltage support | Local monitoring, DER integration | Improves hosting capacity | Medium |

## 6. Case Studies, Challenges, and Future Directions

The advancement of aggregated electric-vehicle (EV) charging networks is not only shaped by technological evolution but also driven by region-specific regulatory, market, and infrastructural conditions. Understanding how different regions have implemented large-scale, cross-operator, and grid-interactive charging aggregation provides essential insights into the scalability and economic potential of such models. This section reviews global practices, identifies persistent constraints, and outlines the next frontiers for intelligent and interoperable charging ecosystems. As summarized later in Table 5, each regional deployment demonstrates distinct operational strategies, levels of digitalization, and measurable value gains.

**Table 5.** Representative Aggregated Operation Case Studies.

| Region | Scale | Dispatching Strategy | Value Improvements | Key Enabling Technologies |
|---|---|---|---|---|
| China | Regional station clusters (hundreds of stations) | Cluster-level load scheduling, shared transformer capacity, cross-brand charger integration | 5-12% peak load reduction, 8-15% charger utilization improvement | Interoperability protocols, centralized dispatch platform, real-time load forecasting |
| EU | Multi-country virtual networks (dozens to hundreds of stations) | Standardized communication, roaming-enabled load management | Improved cross-operator utilization, enablement of flexibility markets | OCPP 2.0.1, ISO 15118, unified billing & settlement |
| USA | Fleet-based clusters (tens to hundreds of depots, thousands of chargers) | Predictive fleet scheduling, V1G/V2G participation, demand response optimization | Revenue from ancillary services comparable to charging fees, peak shaving, reserve provision | Fleet management systems, aggregator platform, real-time market interface |

*6.1. Global Case Studies*

6.1.1. China

China has become one of the most active markets in experimenting with aggregated charging models due to its high EV adoption rate and strong policy push for interoperability. Provincial-level operators have begun deploying regional station-cluster scheduling, where multiple stations under different brands feed into a unified dispatching platform. Through shared transformer capacity, cross-brand charger onboarding, and real-time utilization balancing, several pilot cities report a 5-12% reduction in peak-hour load pressure and 8-15% improvement in charger utilization, particularly in mixed public-private networks. Data-layer convergence-supported by national-level interoperability guidelines-lays the foundation for scalable aggregator operations.

6.1.2. European Union

The EU's advancements are largely propelled by standardized communication protocols, most notably OCPP 2.0.1 and ISO 15118-20, which enable seamless charger roaming across operators and countries. Unified authentication and settlement systems make large-scale "virtual charging networks" feasible, where diverse stations form a de facto federated infrastructure. Several cross-border projects have demonstrated pan-European aggregator platforms capable of dynamic load control and participation in local flexibility markets. The European model emphasizes compliance, transparency, and market compatibility, providing a blueprint for interoperable charging ecosystems with high regulatory maturity.

6.1.3. United States

The U.S. market demonstrates a more market-driven trajectory, with several aggregators and charging operators already participating in ERCOT and CAISO ancillary service markets. Fleet operators (e.g., logistics, ride-hailing, and municipal fleets) are central to U.S. aggregation strategies because of their predictable schedules and large controllable load. Pilot projects show that aggregated charging clusters can provide demand response, peak shaving, and reserve capacity, sometimes yielding higher value streams than traditional charging fees. While interoperability across networks is still evolving, the U.S. provides strong evidence that aggregated charging can be an economically meaningful grid service provider.

A comparative summary of these representative cases-including region, operational scale, scheduling algorithms, value improvements, and enabling technologies-is presented in Table 5.

### *6.2. Key Challenges*

Despite promising results across global pilots, several systemic challenges continue to constrain large-scale deployment:

#### 6.2.1. Interoperability Limitations and Protocol Fragmentation

Although standards such as OCPP and ISO 15118 exist, many operators rely on customized implementations, creating protocol inconsistencies and data islands. Cross-platform charger onboarding remains labor-intensive in many regions.

#### 6.2.2. Scalability of Real-Time Dispatching Algorithms

Aggregators managing thousands of chargers face exponential computational complexity. Algorithms for power allocation, constraint satisfaction, and demand response must operate with millisecond-level latency while integrating uncertain factors such as EV arrival times and mobility behavior.

#### 6.2.3. Immature Business Models and Uneven Tariff Mechanisms

In many markets, revenue models for flexibility services remain underdeveloped. Lack of clear price signals, inconsistent demand response policies, and regional tariff heterogeneity weaken operator incentives to adopt aggregated operation.

#### 6.2.4. Data Privacy and Cybersecurity

Large-scale aggregation requires extensive data exchange-vehicle identifiers, user behavior, charging curves, and power system parameters-which increases vulnerability to cyberattacks. Ensuring secure data governance is becoming a precondition for market expansion.

### *6.3. Future Directions*

Looking ahead, the aggregated charging model is expected to evolve toward more intelligent, integrated, and cross-sectoral configurations.

• LLM-enhanced optimization for V2G and scheduling.

Large language models (LLMs) and foundation models can support adaptive load forecasting, constraint-aware dispatching, and anomaly detection, reducing computational burdens and increasing grid responsiveness.

• Digital-twin-driven operational decision-making.

High-fidelity digital twins of charging stations, grid nodes, and mobility patterns will enable real-time simulation of thousands of dispatching scenarios, offering operators unprecedented visibility into capacity risks and scheduling outcomes.

• Ultra-large-scale aggregation in the autonomous fleet era.

Autonomous taxis and logistics fleets will exhibit highly predictable charging cycles, enabling city-scale orchestration of tens of thousands of EVs. This shift could turn aggregators into major grid flexibility providers.

• Cross-energy-system coordination (electricity-heat-storage-mobility).

Integrated energy systems will allow EVs to interact not only with the power grid but also with thermal storage, district heating, and distributed renewable assets. Such sector coupling can significantly increase local hosting capacity and resilience.

## 7. Conclusion

The aggregated operation model represents a pivotal approach for enhancing the value and efficiency of electric vehicle (EV) charging infrastructure. By integrating multi-station, multi-brand, and multi-operator networks, aggregation enables a more flexible and intelligent allocation of charging resources, overcoming the limitations of traditional station-level deployment such as low utilization rates and delayed return on investment. Through coordinated load management, capacity optimization, and demand forecasting, aggregated systems can achieve significant improvements in operational efficiency, cost reduction, and service quality.

A combination of advanced methods—including machine learning-based demand prediction, optimization algorithms for infrastructure and operational planning, and digital twin simulations—provides a robust framework for decision-making at both strategic and real-time levels. Moreover, aggregation facilitates multi-stream revenue generation, encompassing charging fees, dynamic pricing, ancillary services, and vehicle-to-grid (V2G) participation, thereby unlocking new economic value for operators. The synergistic implementation of CAPEX and OPEX optimization strategies further enhances the financial sustainability of charging networks.

Looking ahead, the development of intelligent station clusters, large-scale V2G integration, and AI-driven operational control offers promising prospects for next-generation EV infrastructure. Cross-energy system coordination, automated fleet management, and predictive analytics will enable more resilient and adaptive networks capable of responding to dynamic grid requirements and fluctuating user demand. While challenges such as interoperability, data security, and scalable real-time dispatch remain, the aggregated operation model clearly establishes a strategic pathway toward maximizing asset utilization, operational flexibility, and economic benefits in sustainable EV charging infrastructure.

## References


1. D. Yan, C. Ma, and Y. Chen, "Distributed coordination of charging stations considering aggregate EV power flexibility," IEEE Transactions on Sustainable Energy, vol. 14, no. 1, pp. 356-370, 2022. doi: 10.1109/tste.2022.3213173
2. X. Shi, Y. Xu, Q. Guo, and H. Sun, "Optimal dispatch based on aggregated operation region of EV considering spatio-temporal distribution," IEEE Transactions on Sustainable Energy, vol. 13, no. 2, pp. 715-731, 2021. doi: 10.1109/tste.2021.3130547
3. A. T. Lemeski, R. Ebrahimi, and A. Zakariazadeh, "Optimal decentralized coordinated operation of electric vehicle aggregators enabling vehicle to grid option using distributed algorithm," Journal of Energy Storage, vol. 54, p. 105213, 2022. doi: 10.1016/j.est.2022.105213
4. C. B. Saner, A. Trivedi, and D. Srinivasan, "A cooperative hierarchical multi-agent system for EV charging scheduling in presence of multiple charging stations," IEEE Transactions on Smart Grid, vol. 13, no. 3, pp. 2218-2233, 2022. doi: 10.1109/tsg.2022.3140927
5. B. Jie, J. Baba, and A. Kumada, "Contribution to V2G system frequency regulation by charging/discharging control of aggregated EV group," IEEE Transactions on Industry Applications, vol. 60, no. 1, pp. 1129-1140, 2023. doi: 10.1109/tia.2023.3292814
6. L. Wang, J. Kwon, N. Schulz, and Z. Zhou, "Evaluation of aggregated EV flexibility with TSO-DSO coordination," IEEE Transactions on Sustainable Energy, vol. 13, no. 4, pp. 2304-2315, 2022. doi: 10.1109/tste.2022.3190199
7. Z. Ye, Y. Gao, and N. Yu, "Learning to operate an electric vehicle charging station considering vehicle-grid integration," IEEE Transactions on Smart Grid, vol. 13, no. 4, pp. 3038-3048, 2022. doi: 10.1109/tsg.2022.3165479
8. H. Jin, S. Lee, S. H. Nengroo, and D. Har, "Development of charging/discharging scheduling algorithm for economical and energy-efficient operation of multi-EV charging station," Applied Sciences, vol. 12, no. 9, p. 4786, 2022. doi: 10.3390/app12094786
9. S. Gao, H. Li, J. Jurasz, and R. Dai, "Optimal charging of electric vehicle aggregations participating in energy and ancillary service markets," IEEE Journal of Emerging and Selected Topics in Industrial Electronics, vol. 3, no. 2, pp. 270-278, 2021. doi: 10.1109/jestie.2021.3102417
10. C. O'Malley, L. Badesa, F. Teng, and G. Strbac, "Frequency response from aggregated V2G chargers with uncertain EV connections," IEEE Transactions on Power Systems, vol. 38, no. 4, pp. 3543-3556, 2022.
11. M. M. Hoque, M. Khorasany, R. Razzaghi, M. Jalili, and H. Wang, "Network-aware coordination of aggregated electric vehicles considering charge-discharge flexibility," IEEE Transactions on Smart Grid, vol. 14, no. 3, pp. 2125-2139, 2022. doi: 10.1109/tsg.2022.3204761

12. T. Long, Q. S. Jia, G. Wang, and Y. Yang, "Efficient real-time EV charging scheduling via ordinal optimization," IEEE Transactions on Smart Grid, vol. 12, no. 5, pp. 4029-4038, 2021.
13. J. Zhang, L. Che, X. Wan, and M. Shahidehpour, "Distributed hierarchical coordination of networked charging stations based on peer-to-peer trading and EV charging flexibility quantification," IEEE Transactions on Power Systems, vol. 37, no. 4, pp. 2961-2975, 2021. doi: 10.1109/tpwrs.2021.3123351