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Charging governance and infrastructure sizing for electric fleets: technical foundations, demand management and operational reliability

Governança de recarga e dimensionamento de infraestrutura para frotas elétricas: fundamentos técnicos, gestão de demanda e confiabilidade operacional

Gobernanza de recarga y dimensionamiento de infraestructura para flotas eléctricas: fundamentos técnicos, gestión de la demanda y confiabilidad operativa

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Abstract:
Charging is the primary coupling point between electric fleets and the power system, turning a mobility challenge into one of energy, power, and reliability. In utility operations, charging infrastructure functions as a mission-critical system because it defines operational windows, constrains uptime, and shapes total cost through capital investments, time-varying tariffs, and coincident peak demand. A technical-operational assessment requires separating energy from power and recognizing that nominal charger ratings rarely match effective absorbed power, since battery management system (BMS) constraints and CC–CV dynamics (constant current–constant voltage) govern charging behavior, especially under thermal variability. Fundamentals of AC and DC charging are consolidated and electrical, electrochemical, and risk-management implications for infrastructure sizing are discussed. Integrated fleet planning approaches are examined, emphasizing models that jointly consider vehicle schedules and charger deployment, as well as coordinated charging (smart charging) under unidirectional control (V1G) and bidirectional operation (V2G, vehicle-to-grid), accounting for grid impacts. Interoperability and communication are treated as engineering requirements, highlighting IEC 61851, ISO 15118, and OCPP as complementary layers. EVSE reliability and maintenance, along with cybersecurity in connected charging ecosystems, are addressed as determinants of real-world availability at scale, leading to a conceptual framework for defensible technical-operational decisions without reliance on proprietary case studies.

Keywords:
charging infrastructure; electric fleets; sizing; coordinated charging; ISO 15118; OCPP; reliability; V2G.

Resumo:
A recarga constitui o principal ponto de acoplamento entre frotas elétricas e o sistema elétrico, convertendo um desafio de mobilidade em um problema de energia, potência e confiabilidade. Em operações utilitárias, a infraestrutura de recarga configura-se como sistema crítico, pois define janelas operacionais, condiciona a disponibilidade e influencia o custo total por investimentos, tarifas horárias e demanda coincidente. A análise técnico-operacional requer distinguir energia de potência e reconhecer que a potência nominal do carregador raramente coincide com a potência efetivamente absorvida, dado que limites do sistema de gerenciamento de bateria (BMS, battery management system) e a dinâmica CC–CV (constant current–constant voltage) modulam o processo, sobretudo sob variabilidade térmica. Consolidam-se fundamentos de recarga em corrente alternada e contínua (AC/DC) e discutem-se implicações eletrotécnicas, eletroquímicas e de gestão de risco para dimensionamento. Examina-se, ainda, o planejamento integrado de infraestrutura em frotas, com ênfase em modelos que consideram conjuntamente cronogramas de veículos e carregadores, e estratégias de recarga coordenada

(smart charging) em regime unidirecional (V1G) e bidirecional (V2G, vehicle-to-grid), considerando impactos na rede. Interoperabilidade e comunicação são tratadas como requisitos de engenharia, destacando IEC 61851, ISO 15118 e OCPP. Confiabilidade, manutenção e segurança cibernética são analisadas como componentes da disponibilidade em escala, culminando em um arcabouço conceitual para decisões técnico-operacionais sem dependência de casos proprietários.

Palavras-chave:
infraestrutura de recarga; frotas elétricas; dimensionamento; recarga coordenada; ISO 15118; OCPP; confiabilidade; V2G.

Resumen:
La recarga constituye el principal punto de acoplamiento entre las flotas eléctricas y el sistema eléctrico, convirtiendo un desafío de movilidad en un problema de energía, potencia y confiabilidad. En operaciones utilitarias, la infraestructura de recarga se configura como un sistema crítico, pues define ventanas operativas, condiciona la disponibilidad e influye en el costo total mediante inversiones, tarifas horarias y demanda coincidente. El análisis técnicooperativo requiere distinguir energía de potencia y reconocer que la potencia nominal del cargador rara vez coincide con la potencia efectivamente absorbida, dado que los límites del sistema de gestión de batería (BMS, battery management system) y la dinámica CC–CV (constant current–constant voltage) modulan el proceso, especialmente bajo variabilidad térmica. Se consolidan fundamentos de recarga en corriente alterna y continua (AC/DC) y se discuten implicaciones electrotécnicas, electroquímicas y de gestión de riesgos para el dimensionamiento. Se examina, además, la planificación integrada de infraestructura en flotas, con énfasis en modelos que consideran conjuntamente cronogramas de vehículos y cargadores, así como estrategias de recarga coordinada (smart charging) en régimen unidireccional (V1G) y bidireccional (V2G, vehicle-to-grid), considerando impactos en la red. La interoperabilidad y la comunicación se tratan como requisitos de ingeniería, destacando IEC 61851, ISO 15118 y OCPP. La confiabilidad, el mantenimiento y la seguridad cibernética se analizan como componentes de la disponibilidad a escala, culminando en un marco conceptual para decisiones técnico-operativas sin dependencia de casos propietarios.

Palabras clave:
infraestructura de recarga; flotas eléctricas; dimensionamiento; recarga coordinada; ISO 15118; OCPP; confiabilidad; V2G.

Introduction

Fleet electrification alters the operational control center by replacing rapid and unrestricted energy replenishment with a process conditioned by available time, installed power, and the limits of the electrochemical asset. In electric vehicles, energy is replenished under simultaneous constraints from the vehicle, the charging infrastructure, and the local power grid. This coupling makes availability a systemic outcome: it is possible to have technically adequate vehicles and still operate with low productivity when sizing, load coordination, and interoperability do not keep pace with the scale.

In fleet management, the most critical constraint is usually the power output at the worstcase scenario, not the total daily energy consumption. The temporal coincidence of multiple charging operations within short idle windows increases peak demand, puts pressure on transformers and feeders, and amplifies costs associated with contracted demand and time-ofuse tariffs. Since infrastructure decisions have a long amortization horizon, any underestimation of simultaneity tends to become a persistent bottleneck, while oversizing can compromise economic viability. Therefore, the problem is defined less by "how many chargers" and more by what architecture and capacity support realistic operational windows under varying mission conditions, weather, and tariff policies.

Planning charging infrastructure requires treating location, power, schedules, and charging strategy as interdependent variables, because the technical decision hinges on the intersection between operational window and delivery capacity. In fixed-route systems, the literature shows that more consistent solutions emerge when scheduling, fleet composition, and infrastructure are designed together, since charging time directly competes with the available operating time. The same reasoning applies to yards and depots: end-of-session charge state targets, prioritization rules, and temporal allocation of power reconfigure the necessary capacity, queue formation, and exposure to peak demand.

Beyond the electrotechnical and electrochemical dimensions, recharging has become a digital system. Recharging equipment (EVSE, *electric vehicle supply Equipment (equipment*) depends on communication, authentication, and control to operate with observability and coordination at scale. Interoperability and telemetry consistency become operational requirements: without reliable data on charger status and without command capability, coordinated charging strategies lose effectiveness; without proper maintenance practices, installed power does not translate into available power.

A technical-operational analysis focused on sizing and governance, therefore, needs to articulate three dimensions: fundamentals of alternating and direct current charging and their constraints via BMS; integrated planning under simultaneity and variability; and layers of interoperability, reliability, and security that determine real availability at scale. This foundation allows for the construction of defensible decision criteria without relying on proprietary cases.

2. Technical fundamentals of fleet recharging: energy, power, load curve and BMS constraints.

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Transferring energy from the grid to the vehicle's electrochemical storage involves power electronics control and safety constraints. To understand the impact on fleets, it's helpful to distinguish between two often-confused quantities: **energy** and **power** . Energy measures the total delivered over a period and is expressed in kilowatt-hours (kWh). Power expresses the delivery rate and is expressed in kilowatts (kW). In daily operations, kWh explains the daily volume to be replenished; kW determines whether this replenishment fits within the yard's available time and, consequently, guides decisions regarding power supply, transformation, cabling, and demand contracting.

When recharging occurs using **alternating current (AC, *alternating current) . In AC (current*)** , the AC-DC conversion is done onboard by the onboard charger, and the charging rate then reflects the vehicle's own limits. In ***direct* current (DC *) ,*** the conversion takes place in the external equipment, and the energy enters the vehicle already as direct current, allowing for higher power outputs—with greater cost and complexity, and greater system sensitivity to grid conditions and the charger's thermal control.

In lithium-ion batteries, the charging curve rarely behaves like a straight line. The most common profile follows **DC–CV (constant current–constant voltage *) . current constant voltage*)** : first the current is kept approximately constant; then the voltage is maintained while the current decays. This results in a time asymmetry: reaching a **SOC** (*state of effect) The intermediate state of charge (* STC) tends to be faster than adding the last percentage points, which are extended according to control limits and internal conditions of the cell set. Therefore, SOC targets at the end of the session need to be defined by productivity and risk, and not by a fixed rule of "always charging to the maximum".

battery management system (**BMS)** arbitrates the process . It limits current and power based on temperature, internal voltages, and dispersion between cells, which causes the effectively absorbed power to vary throughout the session. In fast DC charging, the bottleneck can arise in the **pack itself** (the set of cells and modules that make up the vehicle's battery): voltage ceilings in cells, thermal restrictions, and protection logic modulate the actual charging rate. For sizing purposes, the nominal power stamped on the equipment is less important than the effective power under typical operating conditions, because it is this that determines the service capacity within the specified time windows.

The cost of asset degradation throughout its lifecycle is also factored in. Coordinated strategies reduce peaks and costs, but more aggressive rates and remaining in unfavorable SOC/temperature windows shift the durability trade-off. This is where practices like **V2G** (*vehicle - to- grid* , bidirectional operation) require economic and technical governance: potential

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revenue needs to be weighed against the incremental wear and tear associated with its use as a flexible resource.

Closing the system, the electrical installation conditions safety and availability: conductors, protections, grounding, differential devices, and feeder capacity define the actual operating envelope. Since chargers are power electronics loads, they can introduce **harmonics** (distortions in the waveform), affect **power factor** (ratio between active and apparent power), and require attention to **electromagnetic compatibility (EMC)** , that is, operating without interfering with or being interfered with. Coherence between electrical infrastructure, control, and operational windows is what sustains predictable operation at scale.

3. Infrastructure sizing and planning: from the "number of chargers" to the integrated problem of operation and investment.

Choosing the right infrastructure capacity for fleets means ensuring that a set of missions can be fulfilled within time and power constraints, with controlled costs and reliability levels compatible with the operation. The dynamics governing this choice rarely behave well under fixed rules, because simultaneity and variability change the problem's picture according to route, weather, load, and yard discipline. Therefore, planning literature tends to treat the topic as multi-objective: the solution needs to reconcile investment, operational cost, queue risk, availability, and room for expansion, rather than optimizing a single criterion.

In systems where schedules are rigid, the decisive point becomes clear: the time consumed by loading competes with the operational window itself. When scheduling, fleet composition, and infrastructure are planned together, the decision emerges from the ***total cost* of ownership (TCO).** ***of (Ownership*** **)** at the system level, not at the performance level of an isolated piece of equipment. This view explains so-called cross-elasticities: schedule adjustments reduce peak power; increased power decreases reserve fleet; fleet changes alter the need for points; SOC targets at the end of the session reposition bottlenecks. In other words, infrastructure and operation determine each other.

The same logic extends to the discussion about location and capacity distribution. In urban networks, optimal solutions tend to concentrate resources on nodes with greater connectivity and flow, maximizing operational value per installed point. In fleets based on yards and depots, "location" translates into internal architecture: where to position points, how to reduce displacements and maneuvers, how to avoid blockages, and how to decrease unproductive times associated with circulation and coupling. Even when the public network is

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not part of the strategy, the principle remains: installed capacity must coincide with real dwell patterns.

Electrical sizing is also dominated by a specific phenomenon: coincident demand. When many vehicles return to the yard at similar times and start simultaneous sessions, a power peak is formed that puts pressure on transformers and feeders and translates into cost. Time-of- ***use (TOU)*** **tariffs** , in which the price of kWh varies throughout the day, and demand-based charges, where the highest kW peak in a window can determine a significant part of the bill, make this peak more expensive than the total energy consumed. Even with relatively cheap kWh, the kW at the worst moment "buys" infrastructure and tariff commitments for extended periods, making simultaneity control a central objective.

Operational uncertainty prevents the problem from being treated as deterministic. Energy consumption per route varies with weather, topography, cargo transported, traffic, and the use of auxiliary vehicles; dwell times vary with delays and dispatch discipline; and effective loading power varies with vehicle limitations and thermal conditions. Approaches that assume average values tend to fail due to optimism or overestimate due to conservatism. Hence the relevance of models that explicitly incorporate uncertainty, through robust or stochastic optimization, seeking plans that remain viable under realistic variations, rather than being "optimal" only in the central scenario.

As a program evolves from pilot to full scale, simultaneity, available windows, and yard discipline change, altering the regime that underpinned the initial sizing. The fleet grows, practices and training adjust, and the infrastructure begins to operate closer to saturation; consequently, pilot data no longer represent full-scale behavior. Integrated models gain value when they allow testing growth scenarios without linear extrapolations, preserving coherence between installed capacity, schedules, and operational goals, in order to reduce the risk of queues and decreased availability.

4. Demand management and recharge coordination: smart Charging , optimization, and network integration.

With the infrastructure in place, the challenge becomes one of dispatch: deciding **when** and **with what power** each vehicle should charge to complete missions, reducing peak demand, and controlling costs. This field is often described as **coordinated charging** (*smart charging). (charging*), that is, deliberate control of power and timing. Two modalities help to organize the topic. In **V1G** (unidirectional control), only the load is adjusted — time and input power. In

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V2G (*vehicle - to -grid* , bidirectional operation), the export of energy to the grid is also allowed under specific conditions, transforming the fleet into a flexible resource (KEMPTON; TOMIĆ, 2005).

Coordination is often formulated as an optimization problem subject to mission constraints, site power limits, loader capacity, and minimum power requirements per window. Since consumption per route and delays are not perfectly predictable, robust and stochastic approaches become relevant when seeking plans that remain viable under realistic variations, preventing the "optimal" solution in one scenario from degrading into queuing and peak loads when the operational regime shifts. In practice, coordination creates value by exploiting temporal flexibility: shifting load outside peak periods, smoothing coincident demand, and improving the use of installed capacity, provided that operational windows are explicitly defined as problem constraints.

This coordination depends on communication and interoperability. The basic conductive control layer is addressed by **IEC 61851** (general requirements and fundamental charging control). For advanced information exchange between vehicle and infrastructure, **ISO 15118** defines a communication interface that supports negotiation of session parameters and features such as **plug- and -charge** (automated authentication and authorization). **OCPP** (*Open Charge Point Protocol*) structures the communication between the charger and the operator's central system, enabling observability and control at scale. When these layers fail— due to incompatibility, inconsistent implementation, or incomplete telemetry—coordination loses its most important element: the ability to observe the real state and impose power limits predictably.

Alongside interoperability, large-scale operation requires addressing cybersecurity as part of the reliability envelope. In ISO 15118, for example, channel protection depends on **TLS** (*Transfer Logistics Service). Layer Security*), and the **handshake** defines authentication and secure session establishment; weaknesses at this stage can compromise control, authorization, and service availability (KILIC et al., 2024). In operational terms, the point is straightforward: coordination is not just about algorithms; it's about integrating optimization, protocols, data integrity, and risk governance, otherwise instability is possible even with sufficient infrastructure.

5. Reliability, maintenance and safety: the “invisible” side of sizing

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Failures in charging environments and fleets are rarely explained solely by insufficient power. Downtime also stems from inadequate maintenance, low observability , status inconsistencies, and integration weaknesses. When a point goes out of service without rapid detection, the effect does not manifest as an isolated event; it accumulates as an energy deficit, forms queues, compresses windows, and degrades punctuality until it produces operational disruption.

Scaling the infrastructure highlights the hybrid nature of **EVSE** (*electric vehicle supply (equipment*), that is, an electrotechnical system coupled to a digital layer. Electrical failure modes involve contactors, conversion modules, and auxiliary sources; interface failures appear in cables and connectors; protection failures include grounding and differential devices; digital failures arise in software, authentication, communication, and backend . This diversity requires maintenance driven by availability and mean time to repair, with component criticality, modularity, parts inventory, and field technical capacity as design and operational variables, not as afterthoughts (POWELL; JOHNSON, 2024).

Load coordination, in turn, depends on reliable data. Incorrect status—for example, reporting availability in the face of connector failure, session lockup, or loss of communication—compromises power dispatch and leads to decisions based on false assumptions. Charger status auditing needs to have the same rigor applied to vehicle status: telemetry consistency, verifiable alarms, and event trails that explain why a session failed, at what stage, and how much time was lost.

Operating with **direct current at high power levels** implies higher currents and, in many arrangements, higher voltage levels, which increases the system's sensitivity to contact degradation, localized heating, and insulation failures. These conditions require adequate protection coordination, consistent installation criteria, and inspection routines compatible with the usage regime, especially at connection points and elements subject to mechanical and thermal wear. In yards and warehouses, layout decisions also come into play as a technical variable: cable routing, mechanical protection, coupling ergonomics, and internal circulation influence connection times, damage incidence, and the effective availability of points over time.

The digital layer expands the scope of risk when protocols such as **ISO 15118** (vehicleinfrastructure communication) and **OCPP** (*Open Charge Point Protocol , charger*-backend communication) govern authentication and command. In this arrangement, the charger behaves as a network node with an attack surface; implementation and configuration weaknesses can affect service control and continuity, with a direct operational impact (ALCARAZ; LOPEZ;

WOLTHUSEN, 2017). Mitigating this risk requires treating security as an engineering requirement: versioning, hardening , consistent logs, and integration tests that preserve operational predictability.

Sustainable availability in fleets results from resilience: the ability to absorb failures without systemic collapse. Planned redundancy, sufficient observability for rapid diagnosis, and controlled degradation rules allow critical missions to be maintained even with partial loss of points. Coherence between maintenance, data, safety, and contingency policy is what converts installed capacity into effectively available capacity.

6. Final considerations

Considering vehicles, infrastructure, and networks as a coupled system is essential for consistent capacity and operational decisions in electric fleets. At scale, relevant limitations arise less from the daily volume of energy and more from power delivery within real-world windows under conditions of simultaneous operation, thermal variation, and consumption uncertainty. Projections based on averages or static scenarios tend to fail due to optimism (queues and peaks) or conservatism (excessive capex), because they do not represent the worstcase scenario or the dominant operating regime.

Robustness is gained when load coordination is treated as dispatch under explicit mission constraints, site power, and minimum targets per window. By transforming temporal flexibility into a control variable, it becomes possible to reduce coincident demand, stabilize the power profile, and protect punctuality without inflating installed capacity. Sustaining this coordination, however, requires interoperability and observation: coherent communication, reliable telemetry, and effective command capability—conditions without which control strategies rapidly degrade into exceptions and reactive decisions.

It is concluded that defensible sizing and governance decisions require integrating power, operational windows, load coordination, interoperability, reliability, and safety within the same engineering envelope. Without reliable observability and criticality-driven maintenance, installed capacity does not translate into available capacity; without coordination, peaks and queues begin to dictate cost and punctuality. Therefore, scalable operation depends on verifiable design and control criteria—and it is this systemic coherence that sustains availability, predictability, and total cost under field variability.

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