Governing Adaptive Infrastructure Recovery: A Coordination Architecture for Public Electric Vehicle Charging During Outages

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Electrification policy is pushing road transport toward deeper dependence on electricity. Europe has tightened carbon dioxide standards for new cars and vans through Regulation (EU) 2023/851, accelerating coupling between everyday mobility and electricity supply [1]. In many cities, many drivers rely on public charging because they lack private off-street parking or dependable home charging. District-level power disruptions can therefore become mobility disruptions. Yet public electric vehicle charging rarely receives the same institutional attention that emergency planners give to hospitals, water services, and telecommunications. In Germany, critical-infrastructure framing covers energy, transport, health, water, and telecommunications, but charging continuity is rarely treated as an emergency service [2]. Responsibilities are therefore distributed across organisations with different objectives, turning disruption response into a high-stakes cross-organizational coordination problem where legitimacy and authority matter alongside technical restoration [3, 4, 5]. This abstract treats that coordination problem as a project-organizing challenge: how public authorities, distribution-system operators, charge-point operators, mobility actors, communication and payment providers, and users establish shared information, decision rights, and accountability for adaptive recovery during an outage.

This work addresses a specific question: how can cities and infrastructure operators formalise coordination for adaptive recovery of public charging as a socio-technical service during multi-day, district-level outages? It uses the Electric Vehicle Charging Adaptive Recovery System (EVCAR) as an empirical anchor: a recovery-system architecture and controller-independent interface for post-outage public charging, built on a coupled traffic, charging, and power-flow simulation rather than on one artificial intelligence method alone [6, 7, 8]. Within EVCAR, a network-level redistribution role decides where displaced charging demand should go, while district-level charging roles decide how much local service can be safely offered. Different controllers can plug into this interface; published EVCAR work demonstrates the multi-agent learning basis for adaptive charging and cross-district demand redistribution [6, 9].

EVCAR matters here because it makes a governance gap visible. The system defines technical recovery roles, observations, actions, feasibility checks, and logs, but it still leaves open questions that decide whether such policies can be used in the real world: who is authorised to apply which levers, what information is trusted and shared, how priority rules are legitimised, and how communication

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and payment function when power loss also degrades mobile networks. Those "social" questions are not peripheral; they determine whether adaptive recovery helps or harms. In practice, the hardest obstacles are not only technical but socio-technical: adaptive recommendations produced through such a recovery system depend on trusted models and data streams (demand shifts, traffic constraints, and communications/payment degradation) that can drift or fail during outages—so governance must specify what is trusted, how it is validated, and who can pause or override algorithmic recommendations [10, 11]. In engineering-systems terms, the outage response is not a single-asset restoration problem but a coupled socio-technical coordination problem across energy, mobility, digital communication, payment, and user-behaviour subsystems. EVCAR makes this problem concrete because it separates network-level demand redistribution from district-level charging admission, but it does not by itself define which real organisations may authorise, coordinate, override, or audit those decisions.

Key findings from the authors' simulation work to date motivate this coordination focus. District-level outages redistribute charging demand beyond the failed district, static operational responses can reduce one failure mode while shifting stress to another, and the EVCAR interface shows that technical coordination between network-level redistribution and district-level charging decisions is possible but institutionally under-specified [12, 13, 7, 9]. Together, these findings justify treating the missing contribution as a role, authority, and interface map rather than another control-policy result.

The problem: an interdependent system with human behaviour at the centre

A district-level outage changes at least four things at once: first, electricity supply limits what charging can happen, where, and when. Grid operators restore supply in stages, and local constraints shape what gets restored first and what remains constrained. The International Energy Agency argues that power systems need major upgrades in planning and operation to keep pace with electrification [14].

Second, mobility patterns respond immediately. Drivers reroute toward functioning areas, and demand concentrates around remaining chargers, often producing cross-district spillovers and congestion that were not part of normal operations planning [15, 16, 17].

Third, communications shape what people can know and coordinate. Long-duration power failures can degrade mobile networks as backup power runs out, reducing access to route guidance and charger status updates. Germany's Federal Network Agency explicitly warns that large-scale power failures can produce large-scale telecommunications disruption and discusses "basic network" concepts for disaster situations [18].

Fourth, user behaviour determines the lived impact. Empirical work shows heterogeneous preferences for waiting, proximity, and perceived safety, and that heterogeneity matters during outages because some drivers will wait, some will search repeatedly, and some will change plans entirely [19, 20]. These interdependencies interact with distributional justice: access to public charging and charging reliability differ across communities, so recovery choices shape equity as well as efficiency [21, 22, 23].

Public charging recovery is distinctive because the service is public-facing but not usually controlled by one public emergency organization. Charge-point operators, distribution-system operators, mobility agencies, platform and payment providers, and users each control part of the recovery process [24]. A charger may be electrically restored but still practically unavailable if authentication, payment, communication, routing information, or queue management fails. Unlike water or hospital backup services, charging demand can also move across districts in real time, creating new congestion and equity effects where public-charging-dependent users have fewer alternatives.

Why adaptive recovery matters in this setting

Pre-scripted playbooks struggle in systems that evolve hour by hour: grid status, traffic, communications, and behaviour shift in feedback loops. Energy emergency guidance therefore emphasises shared situational awareness, prioritisation, and iterative response actions [25]. Adaptive recovery, as demonstrated through EVCAR, updates coordination decisions as conditions evolve and can surface non-intuitive strategies that reduce unsafe queues, uncertainty, and systematic disadvantage [6]. The organizing challenge is to decide how this changing information becomes accountable action: who can redirect demand, who can alter local charging access, who validates information, and who can pause or override recommendations when conditions or public priorities change.

The contribution: a coordination architecture grounded in “what we need to know”

We propose a human-centred coordination architecture for public charging continuity during district-level power disruptions. The architecture is expressed as three project-organizing interfaces: shared information, authority over recovery levers, and accountable use of adaptive decision support.

1. Shared information layer (“minimum facts”). Define the minimum facts decision makers must share in a crisis, expressed as plain-language coordination questions and shared definitions that work across organisations. The intent is practical interoperability: a minimum operational information set and common definitions for terms that affect decisions, such as available charger, constrained district, priority user, fallback payment, and degraded communications. This is not a new technical standard in this paper.

2. Cross-sector coordination layer (“who can pull which lever”). Clarify who holds authority over which levers: grid restoration actions, traffic management, communications resilience, charge point operations, and priority rules.

3. Adaptive decision-support layer (“how to update decisions”). Use adaptive recommendations that update as conditions change, while keeping humans accountable for value choices. Algorithmic support is one instrument inside governance, not governance itself.

Table 1 operationalises the architecture by grouping the coordination challenge into three elements: governance, information, and adaptive actions, and providing example questions under each. The questions are not “survey items” but prompts for the minimum agreements a city needs to make adaptive charging response workable in practice. They are derived from recurrent interdependence failures in long, district-level outages (information gaps, authority gaps, equity risks) and from the concrete inputs and levers an adaptive tool such as EVCAR requires to be deployable. The table should be read as the detailed question set; Figure 1 later condenses the same logic into the stakeholder and authority-interface map that is the immediate output of this abstract.

Table 1: Coordination interfaces for adaptive charging recovery

Element	**Coordination focus**	**Evidence / validation**	**Coordination artefacts**
Governance (authority & legitimacy)	Who convenes the joint coordination cell; who authorises priority access and public guidance; which equity thresholds are protected across districts and operators.	Policy review, stakeholder mapping, interviews, and Delphi/workshop validation [3, 4, 5, 26].	Role/authority map; escalation triggers; priority/equity policy; decision audit trail.
Information (shared minimum facts)	Minimum situation picture for grid state, charger status, queues, traffic, communications, and payment; common meanings for “available”, “operational”, “queue”, and “access”; fallbacks for degraded connectivity.	Operator data inventory, technical workshops, semantic alignment, and privacy/cyber review [27, 18, 16, 15, 28, 24].	Minimum data set; shared vocabulary; interface specs; low-bandwidth update and payment fallback plan.
Adaptive actions (what can be updated safely)	Which levers may change in real time: public guidance, site rules, routing advice, cross-district load sharing, staffing, or support; when recommendations are approved, overridden, paused, or audited.	Scenario walk-throughs, tabletop exercises, simulation/stress testing, pilot drills, and after-action review [25, 10, 11, 29, 30, 6].	Decision-support protocol; tested playbook; monitoring indicators; integration plan for adaptive tools such as EVCAR.

What the coordination architecture adds beyond EVCAR

EVCAR operationalises the technical recovery layer: it defines the redistribution and district-charging roles, the shared observations and actions, the feasibility checks, and the simulator-facing interface through which different controllers can be tested. The companion learning work then shows that one plug-in controller can learn non-intuitive strategies that help avoid unsafe queues and unstable grid states. But the system also makes explicit what it does not decide. It does not define whose needs count as “critical”, what a fair distribution of access across districts looks like, or who can legitimately instruct operators, traffic teams, and communications systems to act in a coordinated way during an outage.

The coordination architecture proposed here treats those gaps as first-order design requirements. It specifies (i) the minimum shared facts that must be agreed and exchanged across organisations (Table 1), (ii) clear authority over key levers such as priority rules, crowding management, public guidance, and cross-district load sharing, and (iii) conditions under which an adaptive tool’s recommendations can be used, overridden, audited, or paused. Figure 1 then maps those requirements onto the relation between system roles, project interfaces, and real recovery organisations. In other words, the recovery system is an implementation example inside the architecture, not a replacement for it. The implementation challenge, therefore, is not to add more software to EVCAR, but to make these artefacts assignable to organisations before a disruption. That means specifying data-sharing authority, liability, escalation triggers, cross-sector role rosters, fallback communication and payment arrangements, monitoring duties, and transparent priority choices that can sustain legitimacy during disruption.

Triangulation across critical-infrastructure interdependence research, charging behaviour and equity research, public resilience guidance, and the EVCAR system supports a practical claim: governance failures often emerge from missing shared information and unclear authority across systems, even when technical restoration progresses [27, 5, 25, 6]. Taken together, the table and map frame public charging recovery as a concrete instance of a wider authority-interface problem in coupled infrastructure recovery. The transferable issue is not the charging technology itself, but the need to align data, operational levers, accountability, and public legitimacy across actors that do not share a single hierarchy. This framing can travel to other recovery settings where technical operators, public authorities, service providers, and affected users must act on changing information under disruption. This contribution matters for resilience governance because electrification will make public charging a mobility lifeline under high electric vehicle penetration, while electricity systems also face rising demand and tighter operational constraints [14]. It also matters because equity does not “arrive automatically”: if institutions ignore public charging in emergency preparedness, disadvantaged communities can face compounding harms (less access to nearby functioning chargers and fewer information alternatives when communications degrade), and those harms can translate into loss of trust in both infrastructure operators and public institutions [21].

Planned approach and expected outputs

The immediate output is the stakeholder and authority-interface map shown in Figure 1. The figure is the concrete output of this abstract rather than a separate model: it shows how system roles and dependencies, project-organising interfaces, and real recovery organisations must be translated into one another. The map synthesises critical-infrastructure interdependence, electric vehicle charging behaviour and equity, and public resilience guidance, then translates EVCAR recovery roles, inputs, and levers into real-world entities, decision rights, data interfaces, accountability artefacts, and override conditions. Its bottom row gives the concrete map outputs: authority boundaries, operational information, decision and override rules, and public-facing fallbacks. Interviews, workshops, and tabletop exercises are treated as future validation steps rather than completed evidence.

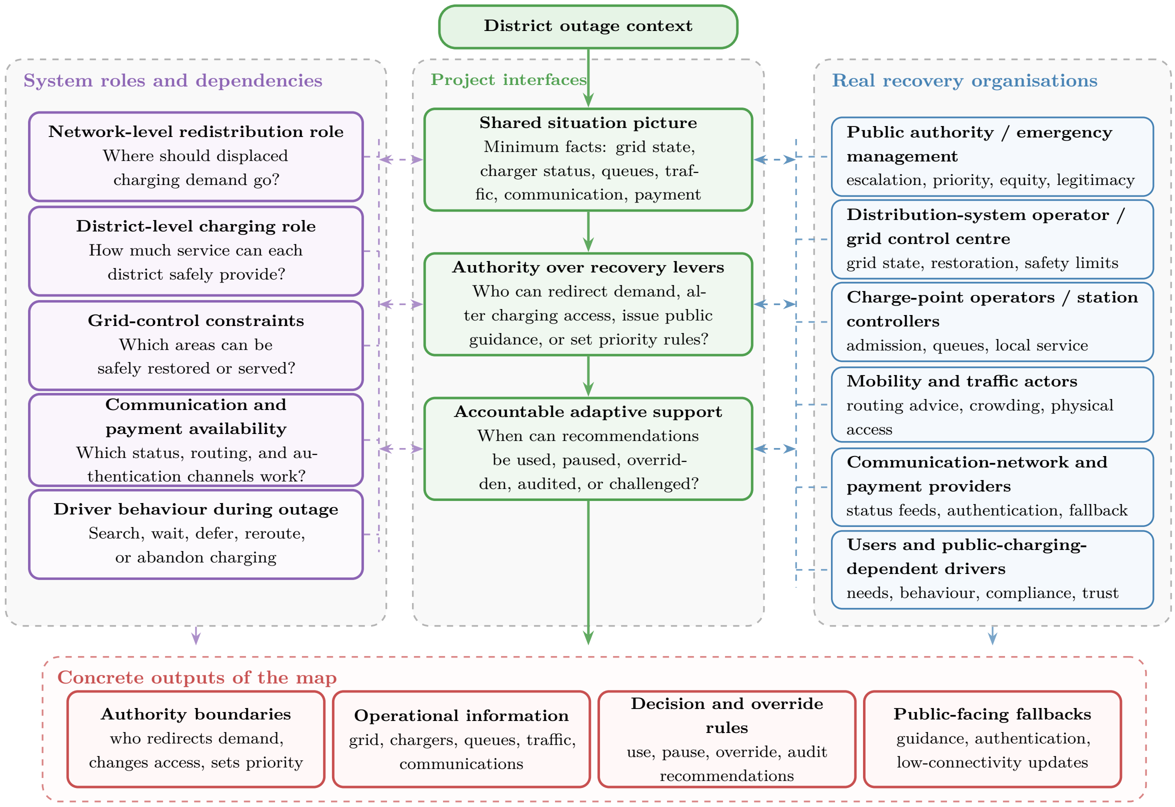

Figure 1: Stakeholder-authority map for adaptive public charging recovery.

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