Applied Energy 421 (2026) 128226

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Urban energy and three-dimensional mobility integration for eVTOL scale-up

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HIGHLIGHTS

- Integrate eVTOLs with urban energy and mobility infrastructure.
- Identifies vertiports as critical coupling nodes for scalable eVTOL deployment.
- Introduces four operational regimes to assess and enhance eVTOL scale-up.
- Presents a research and implementation agenda to avoid bottleneck displacement and ensure reliable scale-up.

ARTICLE INFO

Keywords:
Urban air mobility
eVTOL charging infrastructure
Distribution grid deliverability
Energy-mobility coupling
Integrated power-transport planning

ABSTRACT

Cities are undergoing an energy and mobility transition as buildings and transport electrify under congestion, land scarcity, and tightening constraints on emissions, noise, and air quality. Electric vertical take-off and landing services extend mobility and time-sensitive logistics into a third dimension, but city-scale deployment hinges on synchronizing operations with local electricity deliverability and surface access capacity. We frame the vertiport as an urban energy–mobility interface node where schedules and turnaround rules concentrate curbside arrivals and high-power demand on specific feeders. Feasibility is governed first by local distribution-grid deliverability at operational timescales, subject to power-quality limits, and by curbside and transfer throughput, rather than annual energy accounting or nameplate ratings. High-throughput operations create megawatt-scale charging pulses, while weather, temporary restrictions, and access disruptions shift and re-cluster peaks through diversion and recovery. We show how access variability can amplify charging coincidence and how power caps can propagate into curb congestion, explaining why pilots can succeed yet scale-up becomes upgrade-intensive once siting decisions and service commitments are locked in. This article offers a conceptual and strategic perspective that recasts the vertiport as an urban energy–mobility interface whose reliable scale-up is governed by local deliverability and access constraints at operational timescales. On that basis, we classify coordination regimes that stall or enable reliable scale-up and distill a staged agenda for interface diagnostics, coupled planning, threshold-based deployment, and coordinated operations.

1. Introduction

Cities are electrifying mobility and buildings while operating under binding constraints from congestion, carbon targets, land scarcity, and tightening local requirements on air quality and noise [1]. Electric vertical take-off and landing services are increasingly framed as a three-dimensional mobility layer that can complement mass transit and reshape access to airports and secondary centers. Yet public and policy debate remains dominated by aircraft performance, certification, and cost drivers, with urban infrastructure interfaces treated as downstream implementation details. Related reviews and planning studies have advanced discussions of aircraft capability, market development, and vertiport siting, but they often treat deliverability and surface access as adjacent considerations rather than as coupled, time-local constraints

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https://doi.org/10.1016/j.apenergy.2026.128226
Received 1 March 2026; Received in revised form 15 May 2026; Accepted 8 June 2026

that determine reliable scale-up.

This perspective argues that reliable scale-up, understood here as sustained throughput expansion without recurrent interface breakdown or erosion of delivered service reliability, will be governed less by aircraft performance alone than by whether cities can provide reliable capacity at the local deliverability and access interfaces through which vertiports interact with incumbent systems. A vertiport is not only an airside facility. It is an urban energy–mobility interface node that simultaneously draws on deliverability for rapid charging and on surface access throughput for arrivals, departures, and curbside processing [2,3]. At high-throughput sites, operationally constrained turnarounds can compress charging into short intervals and expose time-local scarcity on specific feeders and transformers under shared power-quality and reliability constraints. These constraints arise within a metropolis that is already electrifying road transport and commercial fleets, so the limiting factor is often local headroom in critical windows rather than citywide energy totals.

The flight segment is only one component of delivered performance. End-to-end reliability depends on how consistently travelers and parcels can reach the site, clear curbside processes, and connect across modes [4]. Access unreliability can concentrate arrivals in time, compress effective turnarounds, and increase charging coincidence even at locations that appear adequate under static screening. Conversely, deliverability limits can lengthen ground time and increase landside occupancy, feeding back into curb congestion and local traffic reliability. Scale therefore requires deliverability, access capacity, and operating windows to be governed within one integrated service with aligned responsibilities, control authority, and shared performance targets.

Relative to earlier discussions of eVTOL infrastructure and vertiport planning, this perspective focuses on the coupled interface through which local distribution-grid deliverability and surface access throughput jointly govern reliable scale-up. Its primary contribution is conceptual: it redefines the vertiport from a standalone aviation asset to an urban energy–mobility interface and uses that reframing to explain how charging coincidence, access variability, and recovery dynamics generate localized bottlenecks that shape siting, phasing, and coordinated operations. This perspective is intended as a conceptual and strategic contribution for planners, grid stakeholders, operators, and policymakers, not as a city-specific operational assessment or a quantitative planning framework. The sections that follow map the coupled urban architecture, trace how uncertainty and recovery produce megawatt-scale charging pulses and shifting peaks, and use siting lock-in and asymmetric coupling to explain why scale-up can fail late unless coordinated planning and operations are introduced early [5–7].

2. A systems view of urban energy–mobility integration

In a mature urban deployment, eVTOL services become a routine component of urban mobility and time-sensitive logistics, supported by a network of vertiports co-located with major transport and service nodes [8]. What limits performance is not the airborne segment alone, but the coupling among low-altitude traffic operations, surface access capacity, and distribution-grid deliverability at each node. Vertiports mediate this coupling by translating schedules and turnaround policies into time-compressed arrivals and high-power charging events. Fig. 1 summarizes the coupled architecture and the touchpoints where impacts first materialize on the surface network and the distribution grid.

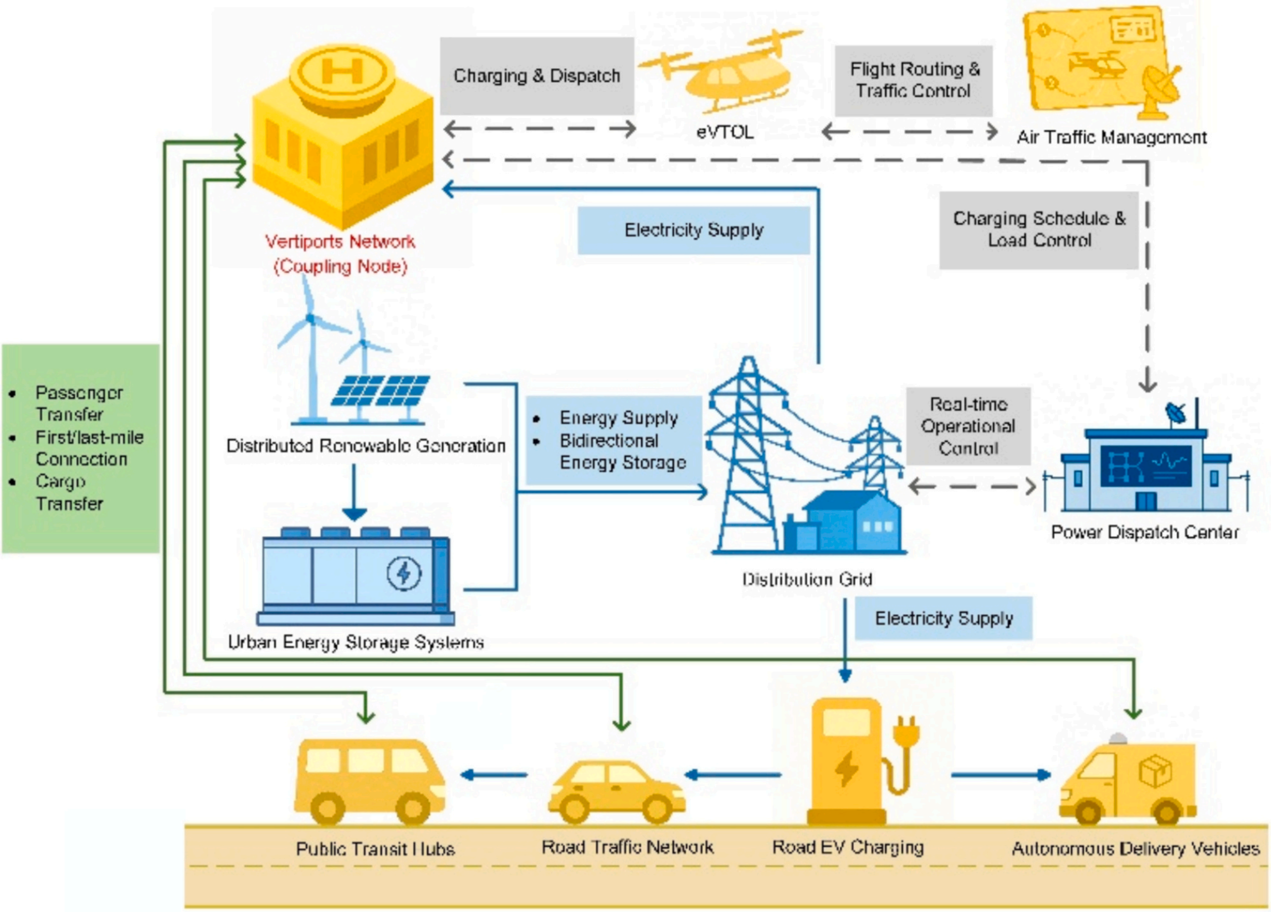

Fig. 1. Vertiports as urban energy–mobility interface nodes linking low-altitude operations, surface access, and distribution-grid deliverability. The schematic identifies the primary interfaces through which localized surges propagate across the road network and the distribution grid.

Sections 2.1 and 2.2 characterize the node-level subsystems and the localized touchpoints through which cities first experience the coupling at operational timescales. Section 2.3 then synthesizes the interface logic that motivates the subsequent discussion of dynamic demand and uncertainty. As the network scales, reliability and throughput are governed less by pad counts or charger nameplates than by the ability of these interfaces to absorb short-duration surges without cascading delays.

2.1. *Vertiports as the energy–mobility nexus*

At city scale, the relevant unit of design is the vertiport as an urban energy–mobility interface node, where airside operating windows couple two incumbent infrastructures: the surface transport network that delivers passengers and parcels, and the distribution grid that supplies energy for rapid turnarounds. Airside rules and recovery procedures determine the time windows over which arrivals must be processed and energy must be delivered, thereby mapping schedule structure into concentrated demands on curb throughput and local distribution headroom. Accordingly, treating the aircraft in isolation obscures the binding constraints that govern feasibility at scale [9]. We therefore describe each vertiport as a tightly coupled combination of three subsystems: the airside operating subsystem, the landside access subsystem, and the energy interface subsystem.

The airside subsystem governs stands, pads, and turnaround rules. Throughput is shaped by the sequencing of arrivals and departures, ground handling processes, and contingency procedures under weather variability and temporary operating restrictions. These choices define the operational windows within which energy must be delivered and within which surface arrivals must be processed. Airside decisions therefore map directly into loading patterns on the other subsystems. For eVTOL services, safety margins and battery thermal management, together with tight turnaround targets, tend to harden these windows and limit the extent to which charging can be deferred without degrading throughput or schedule integrity.

The landside access subsystem connects the vertiport to the multimodal surface network. Access is a capacity interface with identifiable short-duration bottlenecks, most commonly curbside pick-up and drop-off, staging for ride hailing and shuttles, pedestrian links, and transfer corridors to bus and rail. At high demand nodes, binding constraints are often governed by curb turnover and intersection delay rather than average daily traffic conditions [10]. These constraints shape the temporal distribution of arrivals and, in turn, the degree of synchronization in turnarounds and charging demand.

The energy interface subsystem connects the vertiport to the distribution grid. This interface is defined not only by connected load and transformer ratings, but also by deliverability constraints that bind at operational timescales. These include feeder headroom, voltage regulation limits, protection coordination, and power-quality requirements [11]. Depending on site design, on-site storage and power conditioning can shape net withdrawals to better align with local headroom. Importantly, this subsystem is typically managed by entities different from those responsible for landside traffic management. Interconnection planning and distribution upgrades involve different timelines, stakeholders, and approval pathways than curb management and station area traffic control. As a result, the architecture inherently spans multiple jurisdictions and responsibilities even when the physical node is singular.

At the network level, nodes form corridors and clusters rather than isolated points [12,13]. Some are integrated with major surface hubs, others serve district access, and others support specialized applications in logistics, healthcare, or critical services [14]. This distinction matters because it changes which interface becomes binding first and how constraints propagate across the network. Such interface pressures are likely to be most acute at high-throughput passenger nodes, whereas lower-utilization or specialized sites may encounter different first-binding interfaces. It also provides a structural explanation for why early pilots can appear successful while scale-up remains vulnerable to localized capacity limits.

2.2. *Where cities feel the coupling first*

Because vertiports simultaneously draw on surface access capacity and deliverability, impacts on incumbent infrastructures typically emerge at localized touchpoints rather than in citywide averages. These touchpoints interact through feedback between arrival timing, turnaround occupancy, and charging coincidence. On the distribution grid, the earliest pressure often concentrates on assets serving the node, most notably the transformer and feeder segment that provide headroom, associated voltage control equipment, and protection settings that must accommodate rapid changes in demand without compromising reliability or power-quality. As multiple nodes expand within the same metropolitan area, impacts can accumulate in spatially clustered patterns that reflect the topology and operating margins of the local distribution network.

On the surface network, impacts first appear where time-compressed arrivals meet finite processing capacity. Key touchpoints include curbside pick-up and drop-off, staging areas, pedestrian pinch points, and adjacent intersections where queues can spill back into the surrounding network [15,16]. At hub integrated sites, transfer corridors and curb management can be limiting. At district sites, local road reliability and staging capacity can be limiting. At logistics-oriented sites, circulation geometry and loading workflows can be limiting, with direct interactions with surrounding traffic.

These touchpoints are coupled. When surface access becomes unreliable due to congestion, inadequate curb management, or disruptions, arrivals tend to become more temporally concentrated. This concentration compresses effective turnaround windows and increases the coincidence of charging events, raising stress on the distribution interface even when nominal flight schedules are unchanged. Conversely, when the energy interface binds through interconnection limits, temporary derating, or conservative power caps, turnarounds lengthen. Longer ground times increase landside occupancy and curb dwell, raising the likelihood of spillback during peak periods. Electrical limitations can therefore manifest as surface throughput problems, and surface throughput limitations can manifest as deliverability problems [17].

eVTOL operations can further synchronize impacts across nodes. Weather deviations, temporary airspace constraints, reroutes, and recovery procedures can retime arrivals across multiple vertiports and concentrate demand into short intervals. Because airspace capacity and separation requirements constrain recovery sequencing, rebound can be concentrated rather than diffuse, amplifying charging coincidence and curb surges precisely when local margin is tight. In a city-scale system, such perturbations are absorbed at the coupled touchpoints of curb throughput and grid deliverability. The remainder of this perspective builds on this architectural view to characterize the resulting loading and uncertainty patterns, identify where planning and coordination are most likely to fail as scale increases, and propose an implementation-oriented agenda linking evidence generation to investment phasing and joint operations.

2.3. *What the interface view adds*

Taken together, Section 2 establishes three points. First, the vertiport is not a standalone aviation asset but an urban energy–mobility interface node formed by the coupling of airside operations, landside access, and distribution-grid deliverability. Second, cities feel scale-up pressure first at localized touchpoints—curbs, transfer corridors, feeders, transformers, and associated control equipment—rather than in citywide averages. Third, these touchpoints interact through feedback: access variability can sharpen charging coincidence, while deliverability limits can spill back into dwell, curb occupancy, and local traffic reliability. This systems view motivates the next section, which focuses specifically on how uncertainty, rebound, and time-local scarcity translate these coupled touchpoints into local deliverability and throughput constraints.

3. Reliability at scale under dynamic urban demand

3.1. Why local deliverability often sets the pace

Many assessments of urban air mobility describe electricity through annual energy use, average emissions intensity, or a representative tariff. These quantities are essential for decarbonization accounting, but they do not determine whether scale is feasible in an electrifying city. What binds first is local scarcity at site-level points of connection, where multiple electrified demands compete for limited operational margin within the same time windows [18,19]. In practice, feasibility is governed by available local headroom and by shared power-quality requirements that protect reliability for other users of the network.

The pulse character of eVTOL charging makes this constraint explicit, particularly at high-throughput, tightly scheduled, and demand-dense nodes where charging and turnaround are strongly coupled. High-throughput vertiports concentrate demand at a small number of sites and compress it into minutes [20]. A single tightly clustered arrival wave can create step changes with fast ramps and low diversity, unlike the smoother aggregation typical of many electrification loads. A stylized example clarifies the mechanism: if several eVTOLs arrive within a narrow 10–15 min window at one vertiport and each aircraft must recover energy before the next scheduled departure, charging demand becomes not only high-power but also strongly synchronized. The result is a short-lived but severe deliverability test at the local point of connection, where feeder headroom, transformer loading margin, voltage regulation, or power-quality limits can bind even though the site's total daily energy remains moderate. In constrained districts, such synchronization erodes operational margin and can degrade service quality through voltage excursions, protection constraints, and power-quality limits. This challenge is more acute than ordinary charging demand assessed at coarser timescales because load diversity is lower, temporal flexibility is constrained by departure commitments, and disruption recovery can re-cluster charging rather than smooth it.

The implication is that vertiport throughput is not determined only by pad counts or charger ratings. It is bounded by a site-specific feasible capacity envelope defined by local margin under shared reliability constraints. Making this envelope explicit shifts planning away from generic electrification assumptions and toward staged, location-aware integration. It also clarifies why flexibility is central rather than optional. At scale, the key question becomes whether charging demand can be shaped across time and across sites through coordinated operations and access design, in addition to electrical measures, so that local scarcity does not force blunt operational caps.

3.2. Uncertainty, coincidence, and shifting peaks

These short-lived charging pulses are further amplified by service design. Wave-clustered arrivals and departures, together with short turnarounds, compress charging into narrow intervals that can coincide with existing urban peaks [21]. Even when daily energy use remains moderate, such coincidence can push local grid and access interfaces into constraint and trigger curtailment, conservative operating limits, or upgrade commitments that dominate cost and timelines. This clustering is not merely an operational preference. It becomes a city-scale infrastructure stressor because it creates synchronized surges in charging demand at the distribution interface and in surface access demand.

Uncertainty makes this coupling harder to manage. Weather variability, temporary restrictions, and access disruptions can shift flows across sites and reallocate demand to locations that were not planned as relief points [7]. Diversions can concentrate arrivals, and recovery actions that clear backlogs quickly can re-cluster departures, creating rebound peaks precisely when local headroom is least available [22,23]. Planning on averages is therefore insufficient for assurance. What governs feasibility is tail risk in coincidence and rebound, not the mean profile [24].

These dynamics also explain why late-stage feasibility checks often fail once siting decisions and service promises are locked in. At that point, remedies collapse to retrofit, throttling, or operationally and contractually costly degradation of the service promise. The binding issue is not distribution planning in isolation, but misalignment across deliverability, access capacity, and operating rules [25]. In that sense, late-stage breakdown is not simply a grid problem or an access problem; it is a coordination failure at the coupled interface. The next section therefore focuses on infrastructure synchrony and how early choices in siting, phasing, access design, and operations can avoid a cycle of repeated stress, retrofit, and degraded service.

4. Scaling traps in coupled urban systems

4.1. Siting lock-in as an early commitment

Siting is the earliest decision that converts an urban vision into commitments that are difficult to reverse, because it fixes where low-altitude operations must be supported by both surface access capacity and deliverability. In practice, site selection is often dominated by demand proximity, real estate feasibility, and airspace convenience, while interconnection feasibility and station-area access are treated as downstream implementation tasks. This sequencing is structurally fragile. The locations that are most attractive to users are frequently those where local electrical headroom is tight and where curbside and transfer capacity is already saturated. When these constraints surface only after agreements are signed and service expectations are communicated, the remaining solution space becomes narrow and expensive.

A credible siting process therefore requires that the two incumbent infrastructure interfaces be treated as first-order feasibility conditions from the outset. The intent is not to apply static pass/fail checks, but to frame each candidate location in time-resolved terms that reflect how deliverability and access performance jointly condition reliable throughput under realistic operating rules. In practice, this means screening attractive sites not only for demand proximity and airspace convenience, but also for paired feasibility. Here, paired feasibility means that access processing and deliverable charging capacity remain jointly supportable during the operational windows that govern throughput. Establishing this paired feasibility framing early preserves optionality in design and sequencing and reduces reliance on late-stage retrofits or blunt operational caps.

The principal failure mode in scale-up is not that constraints exist, but that they are discovered after lock-in has occurred. Interconnection studies, distribution upgrades, and permitting often proceed on timelines that do not match commercial commitments and station-area redesign. Similarly, curb management and transfer improvements can require cross-agency coordination that is not aligned with aviation timelines. When siting is finalized before these constraints are reconciled, late-stage checks tend to force retrofit investment, operational throttling, or degradation of reliability targets. For this reason, siting should be treated as an infrastructure decision governed by coupled feasibility across the grid and the surface network. Section 5.2 specifies the planning workflow and delivery packages that operationalize this principle.

4.2. Asymmetric feedback between access and deliverability

Even when siting is sound, scale-up can fail if surface access and deliverability are managed as independent problems [17]. At a vertiport, these two infrastructures are coupled through time. Surface access determines when passengers, parcels, and ground vehicles arrive and how tightly those arrivals cluster. Distribution deliverability determines whether energy can be supplied within the constrained turnaround window that operations impose. The coupling is asymmetric because small degradations in access reliability can produce large increases in charging coincidence, while electrical mitigation actions often shift congestion and delay back into the access system rather than eliminating the underlying synchrony.

The first pathway runs from access to grid. When curb turnover is limited, transfer corridors are congested, or approach roads are disrupted, arrivals become more time concentrated. Some users arrive earlier to protect punctuality, while others are delayed and then released in waves when queues clear. This concentration compresses the effective turnaround window and increases the overlap of charging events. In turn, local headroom is consumed more rapidly, and deliverability constraints can bind even if total daily energy remains moderate. The consequence is that access unreliability is converted into an electrical peak at the same node and within the same operational window, which intensifies the binding nature of distribution constraints.

The second pathway runs from grid to access. When the energy interface binds, operators respond through power caps, charging queues, conservative buffers, or reduced utilization. These actions protect the electrical interface, but they lengthen ground time and increase landside occupancy. Longer dwell increases curbside dwell and staging demand, and it raises the likelihood of queue spillback into the surrounding road network. The result is feedback that worsens access reliability and further increases temporal concentration, making coincidence harder to manage in subsequent cycles. In dense hub locations, this feedback can shift the dominant bottleneck from electrical headroom to station area congestion, or the reverse, without any improvement in end-to-end performance [26].

This asymmetry explains why single-domain fixes are unreliable at scale. Strengthening interconnection without addressing curbside management can leave the system exposed to access-driven coincidence. Improving access without embedding deliverability into operational rules can produce late-stage throttling at the very locations where demand is naturally concentrated. Managing this coupling requires treating coincidence as a shared constraint and treating recovery as a cross-layer decision, because disruption policies that clear backlogs quickly in the air can create simultaneous curb surges and rapid charging ramps on the ground. Accordingly, scale-up hinges on whether the cross-layer interface is enforced as a binding constraint before demand concentrates in time and place.

4.3. *Operational regimes that stall scale-up*

Urban eVTOL scale-up is governed less by any single subsystem than by how cities govern the coupled access and deliverability interfaces. Fig. 2 summarizes four recurring operational regimes along two attributes that repeatedly shape outcomes in real cities.

The first attribute is energy-interface awareness, meaning that distribution deliverability is treated as binding in siting, phasing, and operations given feeder and transformer headroom, voltage regulation, protection coordination, and power-quality constraints [27,28]. The second attribute is mobility-interface awareness, meaning that curb capacity and access reliability are treated as binding determinants of delivered end-to-end performance.

When neither attribute is treated as binding, deployment follows an uncoordinated build–stress–retrofit cycle: pilots can launch quickly, but expansion fails once demand concentrates. When energy is treated as binding but mobility is not, bottlenecks are displaced rather than resolved; electrically feasible sites can still underperform when access integration is weak, because higher arrival variability compresses effective turnaround windows and increases the coincidence of charging events. When mobility is treated as binding but energy is not, deliverability constraints surface late at dense hubs and trigger throttling through power caps, reduced utilization, or added buffers that degrade throughput and punctuality. Only a fully coordinated regime treats the unit of design as a corridor that couples connection points, access patterns, and schedule structure. It shifts vertiport charging from rigid peak load to dispatchable load that is shaped across time and space through coordinated operations, access design, and site resources, enabling credible scaling under distribution constraints and urban access limitations [29].

In practical terms, the four regimes imply different failure patterns and responsibilities. The uncoordinated regime describes cities where projects can be approved and launched quickly, but scale-up later triggers repeated retrofit cycles. The energy-aware but mobility-unaware regime is typical of sites that can interconnect electrically yet still underperform because curbside, transfer, and arrival processes remain unstable. The mobility-aware but energy-unaware regime captures dense hubs whose access planning is comparatively strong but whose throughput is later capped by local power limits. The coordinated regime is the target condition for reliable scale-up: it treats charging, arrival management, siting, and recovery as corridor-level decisions and

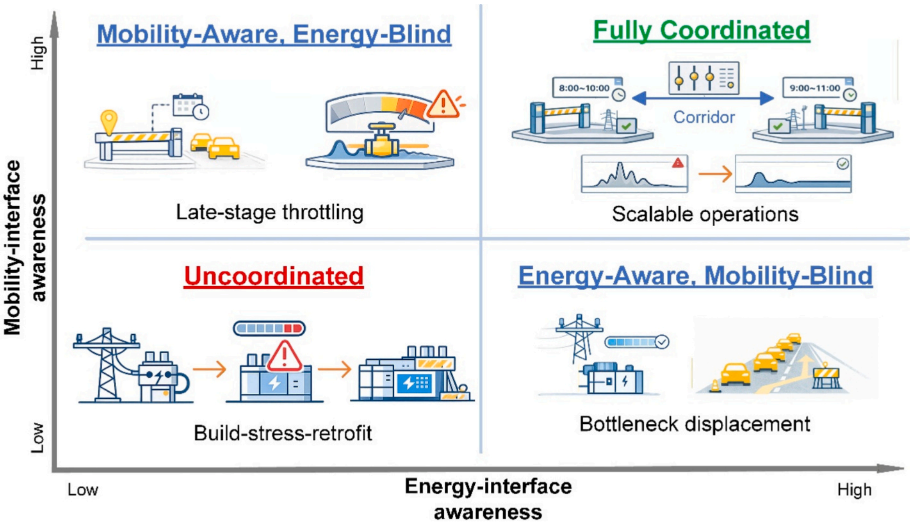

Fig. 2. Four coordination regimes for urban eVTOL scale-up. The figure helps distinguish whether scale-up failure stems primarily from neglected energy constraints, neglected mobility constraints, or insufficient corridor-level coordination across both, and thus what type of intervention is likely to be required first.

provides planners, operators, and grid stakeholders with a shared basis for evaluating vertiports as time-varying interface loads rather than as static additions to annual demand.

5. A research and implementation agenda for city-scale integration

This agenda is organized around decision layers and implementation sequence rather than around individual methods, because scale-up is constrained by what can be observed, approved, and controlled at coupled infrastructure interfaces. The near-term task is to make coupled constraints measurable, comparable, and auditable at candidate nodes through interface diagnostics, minimum reporting requirements, and paired feasibility screening. Only once those constraints are made visible can they be embedded in co-designed siting, interconnection, and station-area planning workflows. Longer-term efforts then concern coordinated operations, pricing, and institutional mechanisms that make flexibility verifiable and enforceable at scale [30].

5.1. Evidence and metrics for scale-ready decisions

The most immediate priority is evidence designed for decisions. A coupling diagnostics layer should express cross-domain constraints in auditable quantities at the operational timescales at which they bind [31].

Diagnostics can begin with representations that translate eVTOL operations into infrastructure loading. Priority building blocks include mission-level energy models across representative profiles, charging power trajectories consistent with battery thermal and aging constraints, and fleet-to-node mappings that convert schedules, turnaround rules, and queue disciplines into minute-scale charging event sequences. Scenario generation and forecasting should explicitly represent weather variability, temporary operating restrictions, and access disruptions, since feasibility is often governed by upper-tail coincidence and rebound [32].

A minimum reporting set should be defined for each vertiport and, where relevant, each corridor or cluster that shares access links and distribution assets [33]. On the electricity side, reporting should quantify time- and location-specific deliverability under power-quality limits. This should be expressed as a charging feasibility envelope linking deliverable power and ramp capability to available headroom on the serving feeder and transformer, subject to voltage regulation, protection coordination, and power-quality constraints [34]. On the mobility side, reporting should quantify peak processing capability at the curb and in transfer corridors, arrival reliability, and spillback risk on approach links. On the operations side, reporting should quantify temporal concentration driven by wave-clustered scheduling, turnaround windows, and recovery policies. These elements should be combined into a joint service feasibility envelope that links throughput targets to both a deliverability window and an access processing window.

Microsimulation and digital twin approaches should translate end-to-end behavior and station-area dynamics into charging events and curb loading trajectories. Reporting should include tail-risk metrics for coincidence, rebound, and displacement, because these tails determine when local scarcity becomes binding. The reporting set should culminate in measurable thresholds that trigger investment actions or operational adjustments, so feasibility is managed through verifiable thresholds [35]. These diagnostics provide the measurable basis for paired-feasibility screening and for the phased planning workflow discussed in Section 5.2.

5.2. Co-designed planning and phased investment

Once interface constraints can be measured consistently, the next step is to operationalize paired feasibility through a single workflow that integrates siting, interconnection, and station-area access design, because scale-up decisions become fragile when these elements advance on misaligned timelines. The point is not to prescribe a single planning tool, but to ensure that site selection, interconnection, and station-area design are evaluated within one time-resolved feasibility logic. In practice, this requires planning tools that couple distribution constraints, station-area access, and operating rules, producing site-specific and corridor-level plans with phasing triggers and accountable delivery packages [36].

Candidate locations should be screened using a paired feasibility test that treats deliverability and access performance as co-equal constraints expressed on operational timescales. The objective is not simply to check whether a site can connect electrically or attract demand, but to determine whether it can sustain throughput at the coupled interface. The deliverability criterion should be expressed as a feasible charging envelope under distribution constraints that bind at operational timescales, including headroom, ramp capability, and power-quality limits on the serving feeder and transformer. The access criterion should be expressed as peak processing capability and spillback risk at the curb, transfer corridors, and approach links. Locations that clear only one criterion should be treated as distinct project types with different approval and delivery pathways and lead times [37].

Planning tools should be coupled across scales to avoid bottleneck displacement. Microsimulation should provide station-area response functions and arrival-to-charging mappings that reflect behavioral adaptation, curbside management, and turnaround rules. Corridor- and city-scale models should represent displacement across nearby nodes, shared feeder assets, and shared access links, so feasibility is evaluated at the scale where scarcity propagates. Investment planning should bundle three elements as one package rather than treat them as separable workstreams: distribution interconnection and, where necessary, reinforcement or adjustments to protection and voltage control; site-side resources and electrical conditioning that shape net withdrawals within verified local headroom and ramp limits [38]; and station-area access interventions that stabilize arrival processes, including curbside management and transfer improvements.

Coordination with other electrified demands and resources should be evaluated explicitly, because eVTOL charging is superimposed on broader urban electrification. Managed charging of road fleets, distributed energy resources, and vehicle-to-grid participation can release local headroom in critical windows, but only when operationally compatible with aviation schedules and verifiable under performance requirements [39–42]. Capacity growth should proceed through phased deployment, with throughput released in tranches only when predefined thresholds are met [43,44].

5.3. Coordinated operations and verifiable flexibility

Over the longer term, once node- and corridor-level feasibility is being diagnosed and planned jointly, operations should make demand dispatchable across time and space because coincidence often becomes the binding constraint at scale. Coordinated operations should be understood as a cross-layer capability for managing when and where coupled demand materializes across the distribution and access interfaces [40]. Operational levers include schedule shaping that manages wave clustering intensity and turnaround timing, charging orchestration that manages power trajectories and queue rules, spatial reallocation across multiple sites within a corridor, and curb management that stabilizes arrivals and prevents spillback. Recovery policies should be evaluated as cross-layer decisions, because actions that clear backlogs quickly can also create simultaneous curb surges and charging ramps.

The objective is not to prescribe a single market or regulatory design, but to ensure that flexibility remains verifiable and that throughput expansion remains coupled to measured interface capacity. In that sense, performance requirements, operating rules, pricing, allocation, and accountability mechanisms should be understood as alternative or complementary ways of enforcing the same principle rather than as a fixed institutional package. Operational and regulatory mechanisms must translate this cross-layer capability into enforceable practice. Flexibility should be specified as a verifiable capability supported by capacity reservation, scarcity-responsive operating rules reflecting location- and time-specific headroom, and performance requirements verifiable at the coupled interfaces. Pricing and allocation mechanisms should internalize local scarcity and rebound risk through time- and location-differentiated signals and performance-linked throughput permissions, while allowing the specific institutional instrument to vary by governance setting. Verification and accountability mechanisms should link payments and operating permissions to measured outcomes, shifting coordination from informal workarounds to auditable commitments and reducing the risk that growth is financed by hidden reliability loss. Resilience should be treated as a cross-layer property, and scale-up becomes conditional on permitting and sustained operability because recurrent, localized impacts at constrained hubs or neighborhoods translate into siting constraints and operational curtailments [45,46]. Whatever the governance setting, the central requirement is verified alignment between throughput growth and measured interface capacity.

Together, these elements align service expansion with verifiable interface capacity on the distribution grid and the surface network, reducing reliance on retrofit cycles and blunt operational caps. These directions therefore clarify the strategic priorities and decision layers for scale-up; they do not substitute for a city-specific operational model or a full optimization framework.

6. Conclusion and outlook

Urban eVTOL will scale only if it is treated as a coupled urban infrastructure service whose reliability is co-produced by deliverability, surface access throughput, and operating rules. The contribution of this perspective is to make that coupled interface—not the aircraft in isolation—the strategic unit of analysis for reliable scale-up. Operationally, eVTOL introduces a three-dimensional mobility layer that couples transport reliability and distribution deliverability at the node interface, making their joint governance a first-order urban performance constraint rather than an aviation add-on. The analysis indicates that feasibility is governed first by time-local scarcity at site-level points of connection rather than by annual energy accounting. High-throughput operations create megawatt-scale charging pulses that bind on local headroom and power-quality limits, while operational variability and access disruptions shift peaks through diversion and recovery. These mechanisms explain why pilots can appear successful yet scale-up becomes upgrade-intensive and prone to reliability degradation once siting and service promises are fixed. The dominant risk is therefore a coordination gap in which coupled constraints are discovered late and managed through retrofit investment or blunt operational caps that erode the end-to-end performance.

Looking forward, the main implication of this perspective is strategic rather than city-specific. Progress depends on elevating both the unit of analysis and the unit of accountability. The unit of analysis should shift from standalone vertiports to corridor and cluster integration, because both distribution constraints and access constraints are spatially correlated and bottlenecks are readily displaced across nearby nodes. The unit of accountability should shift from nominal infrastructure provision to delivered performance at the interfaces, including reliability at the curb and deliverability at the point of connection under credible disruptions. For planners, the central takeaway is that vertiport siting and phasing should be based on paired access–deliverability feasibility rather than on demand proximity alone. For grid stakeholders, the key implication is that vertiports should be assessed as coordination-sensitive, time-local interface loads rather than as generic additions to annual electricity demand. For policymakers, the key implication is that scale-up requires threshold-based approval and cross-agency accountability, because interconnection, access management, and operational scheduling remain institutionally fragmented and are often paced by the slowest institutional interface rather than the fastest technical component.

Methodologically, future work should stress-test coincidence and rebound as explicit tail-risk drivers and develop governance mechanisms that keep capacity growth aligned with verified interface performance. Under those conditions, eVTOL charging can evolve from a rigid peak burden into a coordinated and auditable flexibility service within broader urban electrification, reducing the risk that reliable scale-up defaults to stress, retrofit, and degraded reliability.

CRediT authorship contribution statement

Tao Qian: Writing – review & editing, Writing – original draft, Visualization, Validation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jinyu Yue:** Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Data curation, Conceptualization. **Chongyu Wang:** Writing – review & editing, Resources, Project administration, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jiarong Li:** Writing – review & editing, Visualization, Validation, Formal analysis, Data curation, Conceptualization. **Qinran Hu:** Writing – review & editing, Supervision, Investigation, Funding acquisition, Data curation, Conceptualization. **Hongxun Hui:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work is supported by National Natural Science Foundation of China U24B2081.

Data availability

Data will be made available on request.

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