TYPE Original Research
PUBLISHED 12 January 2026
DOI 10.3389/frsc.2025.1701390

Check for updates

OPEN ACCESS

EDITED BY
Salvador García-Ayllón Veintimilla,
Polytechnic University of Cartagena, Spain

REVIEWED BY
Ural Arslangulov,
University of Sunderland in London,
United Kingdom
Laurencas Raslavicius,
Kaunas University of Technology, Lithuania

*CORRESPONDENCE
Lara Damer
✉ lara.damer@dlr.de

RECEIVED 08 September 2025
REVISED 05 December 2025
ACCEPTED 08 December 2025
PUBLISHED 12 January 2026

CITATION
Damer L, Weiss D and Gruber J (2026) Barriers to fuel cell cargo bike adoption in urban logistics: a multi-level transition analysis.
Front. Sustain. Cities 7:1701390.
doi: 10.3389/frsc.2025.1701390

COPYRIGHT
© 2026 Damer, Weiss and Gruber. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

Barriers to fuel cell cargo bike adoption in urban logistics: a multi-level transition analysis

Lara Damer *, Daniel Weiss and Johannes Gruber

Institute of Transport Research, German Aerospace Center (DLR), Berlin, Germany

European municipalities are increasingly pivotal in advancing sustainable urban freight systems. This paper examines the potential of Fuel Cell Cargo Pedelecs (FCCPs) as innovative alternatives to diesel and battery-powered logistics vehicles. Despite growing technological promise and policy interest in zero-emission logistics, the widespread integration of hydrogen-powered cargo bikes remains limited and underexplored in academic research. Addressing this gap, the study applies a dual framework combining the Multi-Level Perspective (MLP) and Rogers' Diffusion of Innovations theory to analyze both structural and behavioral factors shaping FCCP adoption. Drawing on a mixed-methods assessment of FCCP deployment in multiple cities within the Interreg North-West Europe project, the study systematically contrasts stakeholder expectations and policy visions prior to deployment with operational experiences and institutional realities observed during implementation, enabling identification of mismatches between technical promise and socio-economic constraints. Findings show that while FCCPs can be operated reliably in selected delivery contexts, they did not demonstrate meaningful advantages over conventional electric cargo bikes in real-world conditions. The theoretical benefits of hydrogen, extended range and rapid refueling, were rarely required, while the hydrogen system introduced additional technical, organizational and regulatory complexity. These challenges were amplified by fragmented standards, limited refueling options and elevated insurance and maintenance requirements. Across all MLP levels, misalignments persisted: landscape pressures generated supportive visions, but regime structures and niche conditions did not provide the institutional or infrastructural anchoring needed for broader diffusion. The study contributes to transition research by illustrating how cross-regime niche innovations face compounded alignment challenges.

KEYWORDS

cargo bikes, Fuel Cell Cargo Pedelecs (FCCPs), Multi-Level Perspective (MLP), Rogers' Diffusion of Innovations theory, urban transport, hydrogen mobility, municipal transport policy, zero-emission freight

1 Introduction

Urban logistics systems in European cities are undergoing profound transformations, driven by escalating environmental concerns and changing urban dynamics (Schippl et al., 2016). Traditional diesel-powered freight transport increasingly faces criticism for its significant greenhouse gas emissions, air pollution, and inefficiency in densely populated areas. Consequently, cities are seeking innovative solutions to decarbonize last-mile delivery, improve air quality, and align with European climate targets (Zawieska and Pieriegud, 2018). Among these innovations, cargo bikes have emerged as a promising alternative for urban logistics, offering operational advantages in navigating congested city centers. Recent advances further extend this potential through Fuel Cell Cargo Pedelecs (FCCPs), which combine the flexibility of cargo bikes with the extended range and rapid refueling capabilities of hydrogen fuel cells, as well as the potential to power additional auxiliary consumers such as cabin heating or mobile tool batteries. FCCPs therefore represent a niche mobility innovation that promises to overcome technical disadvantages of battery-powered cargo bikes, such as limited range and long charging times, while maintaining zero emissions.

Yet, as sustainability transition research emphasis, the technical promise of a niche innovation such as FCCPs alone does not determine its capacity to reshape dominant logistics regimes. Within transition frameworks, niche innovations are understood as early-stage socio-technical configurations that develop within protected spaces and may, under certain conditions, challenge or transform incumbent systems (Geels, 2002). For a technology like FCCPs to progress beyond experimental deployment, operational learning must be matched by socio-institutional alignment. Innovations require legitimacy, stakeholder mobilization, infrastructural embedding and alignment with market structures and policy agendas.

In this sense, FCCPs exemplify how technologically promising solutions, even when accompanied by favorable sustainability visions and discourses, can still encounter unforeseen or underestimated barriers when put into real-world practice within urban logistics systems. This fragility and mismatch of expectations is reflected in broader findings from transition studies, which show that many mobility and energy niches generate learning and positive expectations but stall when moving beyond pilot settings (Lovell, 2007; Smith and Raven, 2012). Complementary diffusion research reinforces this pattern, noting that contemporary sustainability transitions increasingly face a problem of diffusion rather than a problem of ecosystems (Gernert et al., 2018), limited user mobilization or institutional barriers rather than technical shortcomings (Fichter and Clausen, 2016; Rennings, 2000; Karakaya et al., 2015). These insights are particularly relevant for FCCPs, whose scaling requires alignment not only within the cycling domain but also across theological developments, hydrogen infrastructure, logistics services and municipal regulation. Comparable cases illustrate how such misalignments produce stalled or constrained transition trajectories. Cycling innovations in Dutch living labs faced fragmented coordination between municipalities and implementation partners, which limited institutional learning (Waes et al., 2021), mirroring governance challenges observed in hydrogen mobility pilots. Community energy projects in the UK regressed once temporary funding ended, revealing the absence of viable models for long-term operation (Hillman and Kirby, 2019), echoing FCCPs' reliance on short-term project financing. In India's net-zero building initiatives, niche development progressed technically but remained constrained by weak policy support and limited coordination among market actors (Jain, 2018). Likewise, heat pump adoption patterns in the UK and Finland demonstrate how user mobilization can shape transition outcomes: limited engagement contributed to stagnation in the UK, whereas active user communities, shared learning and co-innovation accelerated diffusion in Finland (Martiskainen et al., 2021). Other contributions also show that successful pilots do not automatically translate into transformative trajectories, as niche initiatives may be constrained by incumbent influence, unclear market visions or partial institutional (Gernert et al., 2018; Turnheim and Geels, 2019; Markard et al., 2020). Together, this research stresses that socio-institutional fragility, rather than technical feasibility, is often the decisive barrier to niche consolidation. FCCPs exemplify this challenge by requiring simultaneous alignment across cycling, hydrogen and logistics regimes, each characterized by distinct regulatory, infrastructural and market logics.

Because these regimes, as well as operators and users in practice, form expectations and assess technologies differently, understanding FCCP adoption requires examining both anticipated conditions and the realities that emerge once vehicles are deployed in practice (Geels, 2024).

Against this backdrop, our study examines the Interreg North-West Europe FCCP project as a multi-city pilot program aimed at testing Fuel Cell Cargo Pedelecs in diverse logistics applications. Between 2018 and 2023, 35 FCCPs were deployed across Aberdeen in the United Kingdom, Issy-les-Moulineaux in France and Stuttgart in Germany, where they were operated by logistics firms, municipal services and public institutions in parcel delivery, facility management and intra logistics. Because FCCPs operate at the intersection of urban cycling, hydrogen infrastructure and logistics services, they provide a rare empirical testbed for examining how cross-sectoral niche innovations attempt to align with multiple socio-technical regimes simultaneously.

Although FCCP pilots demonstrated technical viability and generated positive expectations (van Biert et al., 2016; Glover et al., 2021), they have not yet secured the infrastructural, regulatory or economic conditions required for durable market formation. Rather than evolving toward commercial uptake, niche development remains heavily reliant on temporary project financing, fragmented implementation networks and loosely coordinated institutional support. A lack of institutionalized knowledge exchange, resulting in key know-how remaining tacit and uncodified, and concentrated among a small number of poorly connected actors. In this sense, FCCPs represent a constrained niche trajectory in which promising technologies encounter socio-institutional hurdles that limit consolidation, even when aligned with decarbonization targets and operational feasibility.

To analyze this constrained niche trajectory, the study combines the Multi-Level Perspective (MLP), which examines structural and institutional transition processes, in the landscape, the regime and niche (Geels, 2002), with Rogers' Diffusion of Innovations theory, which highlights behavioral and perceptual factors shaping adoption (Rogers, 1983). This dual framework follows calls for modular, multi-theoretical approaches in transition research (Geels, 2024) and is particularly suitable for FCCPs because the MLP explains cross-sectoral alignment challenges, while diffusion theory captures user perceptions during attempts to scale, especially through attributes such as relative advantage, compatibility, complexity, trialability and observability (Rogers, 1983; Geels and Johnson, 2018). Together, the two perspectives allow us to link systemic alignment barriers with the practical experiences and evaluations of logistics users during pilot deployment. This provides a more complete explanation of why

FCCPs remain dependent on project settings despite technical viability and favorable sustainability expectations. Accordingly, the empirical design of our study compares ex-ante stakeholder expectations with ex-post experiences gained during real-world pilot testing. This enables the study to assess how regime-level visions and user perceptions evolve when FCCPs move from planning into practice.

The following research questions guide this study:

1. What conditions are required for FCCPs to transition from niche pilot projects to widespread use in urban logistics systems?
2. How can policy measures address barriers to FCCP adoption while supporting innovation in urban transport?

Our findings resonate with and extend existing research on stalled sustainability niches. Similar to cycling living labs in the Netherlands (Waes et al., 2021), FCCPs were hindered by fragmented coordination between municipalities, suppliers and users, which limited institutional learning. FCCPs also experienced governance fragmentation and weak actor alignment, as observed in previous studies such as Jain (2018), alongside diffusion challenges linked to limited user mobilization, similar to findings in Martiskainen et al. (2021). As with community energy initiatives dependent on temporary funding (Hillman and Kirby, 2019), FCCPs lacked viable business models and persistent support mechanisms beyond pilot cycles. Furthermore, legitimacy and vision challenges observed in grassroots initiatives and green building transitions (Gernert et al., 2018; Gibbs and O'Neill, 2015; Turnheim and Geels, 2019) were mirrored in public uncertainty regarding hydrogen safety, insurance risks and economic viability.

The FCCP case contributes three novel insights. First, FCCP adoption requires alignment across hydrogen production, cycling infrastructure and logistics regulation, making niche growth vulnerable to multi regime misalignments rather than barriers within a single system (Geels, 2002; Schot and Geels, 2008). Second, behavioral constraints such as hydrogen risk perceptions, ergonomic limitations and refueling complexity demonstrate that landscape level support for clean mobility does not automatically translate into user adoption, echoing critiques of the MLP for underemphasizing user practices (Shove and Walker, 2010; Sovacool and Hess, 2023). Third, comparing ex ante expectations with ex post practice reveals how visions of FCCPs are recalibrated during use and how redesign, infrastructure standardization and public procurement could reactivate stalled niches, in line with emerging work on recovery pathways (Kern et al., 2020; Turnheim and Geels, 2019). These insights broaden our understanding of niche stagnation by showing how socio institutional misalignments constrain scaling yet may also indicate pathways for renewed niche development, a critical consideration in early transition phases (Geels, 2024).

The paper is structured as follows. Section 2 presents the theoretical framework, combining the Multi-Level Perspective and the Diffusion of Innovations theory to analyze the adoption of FCCPs. Section 3 outlines the background and context of the FCCP Interreg project. Section 4 details the mixed-methods design, including interviews, surveys and insights drawn from an earlier Multi-Actor Multi-Criteria Analysis. Section 5 presents the empirical results from the ex-ante assessment and the ex-post re-evaluation following operational deployment. Section 6 discusses these findings in relation to the analytical frameworks. Section 7 concludes with the main contributions, limitations and an outlook for future FCCP adoption.

2 Theoretical framework: understanding FCCP adoption in urban logistics

This chapter introduces the analytical foundations used to examine FCCP adoption. It outlines the Multi-Level Perspective and Diffusion of Innovations theory, explaining how their combined application enables a systematic assessment of the structural, behavioral and perceptual factors shaping FCCP transition trajectories.

2.1 The Multi-Level Perspective on socio-technical transitions

The Multi-Level Perspective provides a conceptual framework for understanding transitions in socio-technical systems, such as urban logistics (Geels and Ayoub, 2023; Geels, 2002, 2024). MLP distinguishes between three interacting levels:

- **Niches** are protected spaces where radical innovations emerge and develop. They offer shelter from mainstream market pressures and allow experimentation with new technologies like FCCPs.
- **Socio-technical regimes** represent dominant practices, technologies, regulations, and user preferences that stabilize existing systems. In urban freight, the diesel-based logistics regime embodies entrenched infrastructures, norms, and business models.
- **Landscape** pressures refer to external, macro-level forces - such as climate change concerns, EU emission regulations, and societal shifts toward sustainability - that destabilize regimes and create windows of opportunity for niche innovations.

The MLP underscores that transitions unfold through dynamic interactions across multiple levels. As a niche innovation, FCCPs must contend with stabilized regime structures while simultaneously responding to, or benefiting from, broader landscape developments that shape the strategic environment. Assessing this interplay between niche dynamics, regime constraints and landscape pressures is essential for understanding the conditions under which FCCPs may progress, stall or reconfigure during their adoption trajectory.

2.2 Diffusion of Innovations theory

Complementing the structural analysis of MLP, the Diffusion of Innovations theory (Rogers, 1983) focuses on how and why innovations are adopted by individuals, organizations, and societies. Rogers identifies five key perceived attributes that influence adoption rates:

1. **Relative Advantage:** The degree to which an innovation is seen as superior to existing alternatives.
2. **Compatibility:** How well the innovation fits with existing values, experiences, and needs.
3. **Complexity:** How difficult the innovation is to understand and use.
4. **Trialability:** The extent to which the innovation can be tested before full adoption.
5. **Observability:** The visibility of the innovation's benefits and outcomes to others.

Applying these attributes to FCCPs allows for a behavioral and perceptual analysis of their adoption (Sahin, 2006; Gruber et al., 2015).

2.3 Integrating MLP and diffusion theory: a multi-dimensional adoption lens

This study adopts this dual analytical framework that combines MLP with the Diffusion of Innovations theory, responding to calls for modular, multi-theoretical approaches in transition studies that acknowledge both systemic dynamics and actor-level decision processes (Geels and Johnson, 2018; Geels, 2024). The objective is to identify the conditions under which FCCPs may progress from pilot-stage experimentation to wider adoption in urban logistics systems. Because this corresponds to the diffusion phase of transition processes, integrating diffusion theory into the MLP provides a suitable conceptual basis.

The MLP allows us to examine how FCCPs attempt to align with multiple socio-technical regimes, cycling infrastructures, hydrogen mobility systems and logistics service markets, each characterized by distinct actor constellations, regulatory structures and resource dependencies. These structural misalignments help explain why FCCPs face persistent regime-level resistance despite technical viability and supportive sustainability narratives.

Diffusion theory complements this by highlighting how FCCPs are evaluated by users and organizational adopters during real-world trials. Perceptions of relative advantage, compatibility with operational routines, usability and required training (complexity), opportunities for experimentation (trialability) and the visibility of performance outcomes (observability) shaped expectations, business case assessments and post-pilot continuation decisions. These actor-level evaluations help explain heterogeneous adoption outcomes and why experiments did not consistently translate into broader market uptake.

Integrating both perspectives therefore enables a more comprehensive understanding of FCCP adoption dynamics. It clarifies that limited diffusion is not solely the result of structural barriers or regime misalignment, nor solely of user skepticism, but emerges from the interaction of both. By linking cross-sectoral regime dynamics with user-level adoption attributes, this combined framework provides a nuanced basis for analyzing why FCCPs remain a fragile niche innovation and what conditions would be required to support their progression toward durable market formation.

3 Background and case study context

The FCCP project, funded under the Interreg North-West Europe program, aimed to promote sustainable urban freight through the deployment of hydrogen-powered cargo bikes. Running from 2018 to 2023, the project involved the technical development, deployment, and testing of 35 FCCPs across several partner cities, including Aberdeen (UK), Issy-les-Moulineaux (France), and Stuttgart (Germany).

3.1 The Interreg FCCP project: a pilot for hydrogen cargo mobility

FCCPs developed in the project were based on existing heavy-duty cargo bike designs, modified to integrate compact hydrogen fuel cell systems. These vehicles typically featured three or four wheels and a cargo platform capable of carrying up to one Euro pallet. Figure 1 illustrates examples of the FCCP models trialed, including the Bring S by Bayk, the UM CargoBike by Urban Mobility, and the Armadillo by Velove (Figure 2).

The project's objectives were threefold:

- To demonstrate the technical feasibility and operational benefits of FCCPs for urban logistics.
- To identify the barriers to broader adoption from technical, infrastructural, regulatory, and user perspectives.
- To develop and assess policy measures supporting the transition toward hydrogen-powered cycle logistics.

3.2 Trial deployment: cities, use cases, and stakeholders

The FCCPs were deployed between 2021 and 2023 in a variety of around 15 operational contexts across the three participating cities, allowing for the assessment of their performance in different use environments. Deployment scenarios can be categorized along two dimensions:

By type of user:

- **Private sector users:** Cycle logistics companies such as VeloCarrier and messenger Transport and Logistics Berlin integrated FCCPs into their delivery operations. Other participants included delivery services such as Norco Energy and Royal Mail (Aberdeen).
- **Public sector and non-profit users:** Municipal administrations in Issy-les-Moulineaux and Stuttgart, as well as park maintenance teams and educational institutions in Aberdeen, employed FCCPs for internal transport and service trips.

By type of use:

- **Freight trips:** Parcel and goods delivery within urban cores.
- **Service trips:** Transporting tools and equipment for city maintenance or facility management.

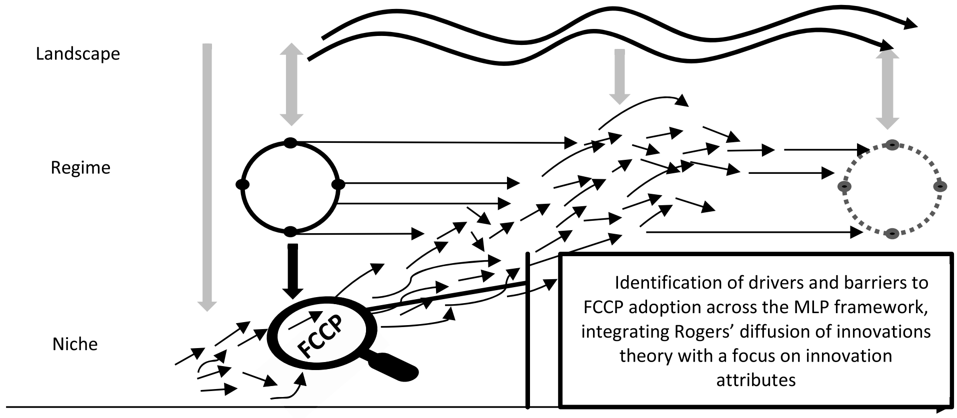

FIGURE 1
FCCPs in MLP and Rogers' Diffusion of Innovations framework (own representation, adapted from Geels, 2002).

FIGURE 2
Three examples of the trialed fuel cell cargo pedelecs: Bring S by Bayk, UM CargoBike by Urban Mobility, Amadillo by Velove (photo: DLR).

- **On-site trips:** Moving materials within larger campuses or municipal service areas.

The diversity of users and applications allowed for a comprehensive evaluation of FCCPs under real-world conditions, capturing insights on both operational benefits (e.g., maneuverability, zero emissions) and practical limitations (e.g., payload capacity, refueling challenges).

4 Methodology

Following established approaches in transition and innovation studies that analyze niche development through mixed-method triangulation (e.g., Waes et al., 2021; Martiskainen et al., 2021), this study employs a mixed-methods research design drawing on multiple data sources to capture the complex and context-dependent dynamics shaping FCCP adoption. This design is well suited to examining how technological expectations, policy visions and organizational intentions formed ex-ante encounter operational, institutional and economic realities during implementation. In doing so, it allows us to systematically compare pre-deployment perceptions with post-deployment experiences and to identify mismatches between technical promise and socio-economic constraints (Figure 3).

4.1 Ex-ante phase: evaluate expectations before deployment

The ex-ante phase combined semi-structured interviews and a focus group discussion with city stakeholders conducted in the

FIGURE 3
Study design (own representation).

three pilot cities. As a preparatory step within the project, a Multi-Actor Multi-Criteria Analysis (MAMCA) (Macharis et al., 2012) had previously been carried out to identify and rank 18 policy measures across several dimensions (Nsamzinshuti et al., 2022). For this study, the MAMCA did not serve as an analytical focus; rather, it provided a structured starting point for the interviews by indicating which measures city administrations and logistics operators initially considered relevant. Building on this baseline, the ex-ante interviews and the focus group enabled us to explore anticipated drivers and barriers for FCCP adoption, expectations around operational performance and infrastructure needs, and the perceived feasibility of different policy measures in the trial cities.

4.2 Ex-post phase: assessing operational experience after deployment

Following the deployment of 35 FCCPs in the participating cities, an ex-post evaluation was conducted to compare real-world experiences with the expectations identified in the ex-ante phase. This phase again employed multiple methods: follow-up semi-structured interviews with municipal officials and logistics providers and users and a concluding focus group to validate and contextualize the findings.

This two-stage design made it possible to contrast initial visions and assumptions with the practical challenges, constraints and learning processes that emerged during actual use. It illustrates how niche innovations, despite strong sustainability narratives, encounter unforeseen or underestimated barriers once they move from protected pilots into real-world operational contexts.

4.3 Analytical value

By integrating qualitative and quantitative evidence across two time points, the study provides a nuanced analysis of the socio-technical, organizational and behavioral dimensions shaping FCCP adoption. The approach offers a grounded empirical basis for understanding why a technically promising niche innovation with strong sustainability appeal struggled to progress beyond pilot-stage experimentation and what this implies for future transition pathways.

5 Results

The results are presented in two steps to reflect the sequential design of the study. First, the ex-ante evaluation examines the expectations, perceived barriers and prioritized policy measures identified before FCCP deployment. This is followed by the ex-post re-evaluation, which assesses how these expectations held up in practice and how real-world operational experience reshaped stakeholder perceptions and policy priorities.

5.1 Ex-ante evaluation of policy measures to promote FCCP adoption

These perceptual tensions were also reflected in the structured prioritization of policy measures derived from the earlier MAMCA exercise. Although the MAMCA itself is not the focus of this study, its results provide a useful empirical starting point for understanding how different stakeholder groups initially evaluated the policy environment for FCCP adoption. The assessment revealed that municipal representatives tended to prioritize measures based on political feasibility and public visibility, attributes closely related to compatibility with existing policy agendas and the symbolic signaling of climate action. Logistics providers, by contrast, emphasized operational reliability and cost efficiency, corresponding to diffusion attributes such as relative advantage and perceived complexity. Despite differing evaluation logics, both stakeholder groups ranked several measures consistently high, including (i) the development of high-quality cycling infrastructure, (ii) disincentives for conventional vehicles such as congestion fees and low-emission zones, (iii) expansion of hydrogen refueling networks, and (iv) communication campaigns to improve public perception of FCCPs (for more information on the MAMCA result see Table A1) (Nsamzinshuti et al., 2022). Taken together, these initial findings form the empirical point of departure for our subsequent analysis. They allow us to position stakeholder expectations within the broader analytical frameworks of the Multi-Level Perspective and diffusion theory, providing a basis for examining how early policy visions did - or did not - align with later real-world experiences.

The three case study cities (Aberdeen, Issy-les-Moulineaux and Stuttgart) illustrate how these expectations were shaped by distinct contextual conditions. Each city entered the pilot with motivations influenced by national strategies and EU-wide decarbonization pressures, which can be interpreted as **landscape-level** drivers within the Multi-Level Perspective. Aberdeen's involvement was linked both to regional sustainability plans and broader EU climate targets. Issy-les-Moulineaux embedded the FCCP trial within its Smart City and digital mobility agenda, aligning local innovation goals with European directives. Stuttgart sought to diversify its traditionally car-focused mobility regime, responding to national decarbonization mandates and overarching EU climate pressures.

At the **regime level**, existing transport systems and policy legacies influenced the degree to which FCCPs could be integrated. Although all three cities had implemented general support measures such as low-emission zones, speed limits, or cycling infrastructure investments, targeted interventions, such as hydrogen refueling stations or dedicated FCCP subsidies, were rare. This reflects a partial misalignment between innovation potential and institutional readiness.

The **niche level**, where FCCPs were positioned as protected experiments, was shaped by stakeholders' expectations about innovation benefits. Here, **Rogers' Diffusion of Innovations** (Rogers, 1983; Lilienthal, 2015) theory helps explain differing perceptions: FCCPs were associated with relative advantages (e.g., clean last-mile logistics, silent operation) and compatibility with existing urban policy goals. However, high perceived complexity (e.g., due to unfamiliar hydrogen infrastructure), low trialability outside pilot programs, and limited observability of outcomes constrained stakeholder enthusiasm.

Intermediate prioritization of municipal fleet use, local funding schemes and continued pilot programs reflected a pragmatic interest in real-world experimentation, while also signaling uncertainty regarding long-term scaling requirements and financial commitments. Spatial planning instruments such as subsidized micro-hubs ranked lower, indicating a preference for immediately implementable measures over longer-term structural interventions whose benefits were perceived as less directly observable. In summary, the ex-ante evaluation showed that landscape-level pressures such as climate policy objectives are increasingly shaping municipal agendas, yet that regime structures remain only partially supportive of hydrogen-based cargo bikes.

5.2 Re-evaluation of policy measures based on operational experience

Following the deployment of FCCPs in the participating cities, a re-evaluation phase was conducted to assess how initial expectations about policy measures held up in practice. This included follow-up interviews and focus group discussions with municipal representatives and FCCP users. The findings are structured along the three levels of the Multi-Level Perspective and interpreted through Rogers' Diffusion of Innovations theory.

At the **landscape level**, broad societal and policy shifts, such as EU climate targets, urban decarbonization agendas, and growing public interest in clean mobility, continued to provide a favorable backdrop for FCCP adoption. These external pressures enhanced the perceived relative advantage of FCCPs by aligning them with climate policy narratives and sustainable urban logistics goals. However, despite this supportive environment, public skepticism toward hydrogen remained a key barrier. Concerns about safety, high refueling costs, and limited insurance options diminished the observability and psychological readiness of users. As supported by recent studies (e.g., Harichandan et al., 2023; Cui et al., 2018), such factors critically influence acceptance, especially for unfamiliar technologies like hydrogen. Thus, while landscape-level momentum exists, its potential is undermined if trust and risk perception are not addressed through targeted awareness efforts.

At the **regime level**, FCCPs exhibited several operational benefits, such as the ability to enter restricted zones and avoid parking constraints. However, these strengths primarily reflect advantages of cargo bike logistics more broadly rather than specific technological benefits of hydrogen propulsion. Crucially, the hydrogen specific improvement potentials that further motivated the niche, such as integrated cabin heating for winter operations or cooling functions for temperature sensitive deliveries, could not be realized within the project period. Despite the long project duration, none of these use cases were implemented, which further reduced the technology's distinct added value compared to conventional electric cargo bikes. Also the systemic obstacles for FCCPs persisted. The dominance of Diesel-based logistics structures continued to discourage transition, and compatibility with existing practices was often low due to fragmented hydrogen refueling infrastructure and interoperability issues between national standards (e.g., German FCCPs vs. French refueling norms). In addition, the absence of a clear regulatory framework and limited financial incentives heightened the perceived complexity and economic risk of FCCP adoption. These barriers suggest that regime-level alignment is incomplete and that regulatory, financial, and infrastructural inertia continue to impede progress.

At the **niche level**, FCCPs were embedded in protected environments (pilot programs, public sector trials, and urban experiments) that enabled limited but valuable learning. In some contexts, such as Issy-les-Moulineaux, FCCPs were successfully integrated into wider hydrogen mobility strategies, which increased public exposure and improved observability. Users cited health benefits and the flexibility of FCCPs in dense urban environments as key relative advantages over vans. Yet several technical and ergonomic limitations constrained broader acceptance. Restricted payload capacity, insufficient suspension comfort and designs that were unsuitable for smaller riders reduced compatibility with diverse user groups and limited everyday usability. Importantly, many of these challenges were not specific to hydrogen technology but reflected more general issues associated with cargo pedelecs. By 2025, this convergence of challenges meant that most FCCPs in the pilot cities were operated exclusively in electric mode. In Issy-les-Moulineaux, incompatibilities between French and German hydrogen standards made refueling impractical, leading the municipality to rely solely on electric operation. A Berlin-based logistics provider experienced an early failure of the hydrogen unit, after which the vehicle continued to function without any observable performance loss. A lack of specialized technical and maintenance personnel also hindered adoption in Aberdeen. At DLR Stuttgart, safety concerns, procedural uncertainties and the absence of convenient refueling infrastructure likewise resulted in FCCPs being used as conventional e-cargo bikes rather than hydrogen-assisted vehicles. This re-evaluation shows that FCCPs continue to face multi-level barriers to diffusion. At the **landscape level**, supportive narratives exist but must be actively reinforced through public engagement and trust-building. At the **regime level**, institutional and infrastructural misalignments must be addressed to lower adoption complexity and increase compatibility. At the **niche level**, technical refinements and more user-oriented pilot designs are needed to improve trialability and user experience.

Drawing on both the MLP and diffusion theory, it becomes clear that mainstreaming FCCPs requires a holistic strategy: one that simultaneously addresses systemic resistance, leverages policy narratives, and improves user perceptions through concrete design and infrastructure improvements.

6 Discussion

The discussion synthesizes the empirical findings with the theoretical frameworks guiding this study. By considering the results through the perspective of Multi-Level Perspective and diffusion theory, this section examines how structural dynamics and user perceptions jointly shape the adoption trajectory of FCCPs. The aim is to explain why certain expectations materialized while others did not, and to identify the conditions that influence whether FCCPs can progress beyond niche experimentation toward broader integration in urban logistics systems.

6.1 Landscape-level pressures and behavioral preconditions for diffusion

At the landscape level, policy frameworks such as the European Green Deal and national decarbonization strategies provided an overarching rationale for FCCP experimentation. These policy drivers were aligned with long-term goals of urban sustainability and served to justify municipal engagement in pilot programs.

Despite this enabling context, behavioral and perceptual factors played a moderating role. Empirical studies suggest that risk perception, trust, and the novelty of hydrogen technologies influence user acceptance, Liu et al., 2023). In the context of FCCPs, concerns regarding hydrogen safety, refueling accessibility, and cost structures affected the broader perception of the technology's relative advantage and observability.

These insights suggest that landscape-level pressures, while supportive, may be insufficient on their own to enable diffusion. The adoption of FCCPs appears to depend on the interaction between macro-level drivers and micro-level perceptions. Public engagement, consistent communication strategies, and transparent reporting of pilot outcomes may support broader familiarity with and confidence in hydrogen-based innovations (Geels and Ayoub, 2023; Apostolou et al., 2021; Lodewyckx et al., 2023).

6.2 Regime-level misalignments and structural barriers

At the regime level, FCCPs were assessed within the broader context of urban logistics systems and institutional structures. Operational benefits, such as improved performance in restricted areas and reduced parking challenges, were acknowledged by participating actors, including logistics providers. Similar findings were noted by Lee et al. (2025), who emphasized that clear operational advantages could facilitate adoption when aligned with regulatory frameworks and market incentives.

Challenges emerged in terms of compatibility, particularly concerning existing logistics routines, vehicle fleets, and refueling infrastructures. Differences in hydrogen refueling standards between countries created interoperability difficulties, complicating cross-border usage and coordination. Such cross-national barriers were consistent with findings in other hydrogen mobility studies, underscoring the need for regulatory harmonization (Pak and Lee, 2024; Kummer and Imre, 2025; Schlund, 2023).

Perceptions of complexity were also present. Uncertainties around regulation, training requirements, and long-term funding introduced institutional constraints that affected stakeholders' willingness to engage beyond the pilot phase. These challenges contributed to limited private-sector engagement and highlighted regime-level inertia, echoing the complexity-related barriers identified by Liu et al. (2023) in the Chinese context.

While FCCPs demonstrated some relative advantages compared to vans, concerns around cost structures, long-term viability, and policy alignment tempered their perceived benefits. In many cases, the limited trialability of FCCPs outside protected environments curtailed broader exposure and institutional adaptation.

A critical finding is that the delivery tasks performed during the pilots did not require extended ranges or uninterrupted operation. Under these conditions, FCCPs were unable to demonstrate a distinct operational advantage over conventional electric cargo bikes within the existing logistics regime. Without a clear performance differential, hydrogen propulsion struggled to justify its additional complexity, cost and infrastructural requirements. These observations indicate that regime-level integration of FCCPs may require not only technological refinement but also policy harmonization, standardization of infrastructure, and comprehensive support mechanisms. Similar recommendations have been proposed by Apostolou et al. (2021) emphasizing coordinated policy support and infrastructure development to facilitate hydrogen mobility transitions.

6.3 Niche-level findings: operational experience and perceived innovation characteristics

Fuel Cell Cargo Pedelecs were introduced in protected pilot environments, such as municipal fleets and service logistics, where users engaged directly with their operational features. In several cities, including Issy-les-Moulineaux and Aberdeen, FCCPs were integrated into broader hydrogen or smart city strategies, which contributed to public visibility and positioned them within a wider narrative of innovation.

From the perspective of Rogers Diffusion of Innovations theory, several innovation characteristics were observed at the niche level. The relative advantage of FCCPs compared to vans was reflected in aspects such as quiet operation, improved access in dense areas, and health-related benefits for users (Apostolou et al., 2021). Their trialability, enabled through publicly supported pilot projects, allowed for limited experimentation, although the temporal and spatial scope of trials constrained broader institutional learning. Observability was facilitated through branding and placement in high-visibility urban contexts, which supported the public perception of hydrogen-based logistics (Sahin, 2006).

Some technical limitations, including restricted payload capacity, limited suspension systems, and ergonomic constraints, affected the compatibility of FCCPs with routine operational needs. Similar challenges regarding technical compatibility and ergonomic design were highlighted by Harichandan and Kar (2023) in their assessment of hydrogen vehicle adoption. Additionally, fragmented certification procedures and support schemes, alongside logistical challenges related to hydrogen infrastructure, contributed to perceptions of complexity among stakeholders and potential adopters.

A central insight emerging from the empirical data is the systematic fallback from hydrogen to electric operation. These cases reveal a central empirical insight. The hydrogen component did not accelerate niche development; it frequently constrained it. Instead of enhancing performance, the hydrogen system reduced trialability, increased perceived complexity and introduced avoidable operational risks. Under the tested conditions, the fuel-cell element limited rather than enabled the diffusion of FCCPs, underscoring the misalignment between the technology's theoretical advantages and its practical utility in current urban logistics environments. This outcome challenges early expectations associated with the FCCP niche and highlights a misalignment between technical promise and socio-technical contexts.

Looking ahead, user feedback pointed to potential design improvements such as temperature-controlled cargo compartments. These features could enhance the relative advantage of FCCPs by expanding their use to temperature-sensitive goods, thereby improving functional compatibility with diverse urban logistics needs. Such refinements could increase perceived value among both users and operators in future niche applications. The adoption trajectory of FCCPs illustrates how the success or failure of green innovations is shaped not only by technological merit but by the interplay of supportive policy frameworks, stakeholder engagement, and systemic readiness (Fichter and Clausen, 2013).

Overall, the findings from the FCCP pilots resonate with broader research on stalled or fragile sustainability niches. Similar to cycling living labs in the Netherlands (Waes et al., 2021), FCCPs struggled with fragmented coordination across municipalities, suppliers and users, which limited institutional learning and hindered iterative improvement. Echoing community energy projects dependent on temporary funding (Hillman and Kirby, 2019), FCCPs lacked long-term financial models and durable support structures beyond project cycles. Comparable to Jain (2018) analysis of net-zero building initiatives, FCCP deployment exposed governance fragmentation and weak actor alignment, producing slow or inconsistent progress. In line with diffusion studies showing the importance of user mobilization for heat pump uptake (Martiskainen et al., 2021), FCCPs demonstrated that limited user engagement and operational uncertainty can significantly constrain niche development. Moreover, legitimacy and vision challenges, documented in grassroots innovation and green-building transitions (Gernert et al., 2018; Turnheim and Geels, 2019; Gibbs and O'Neill, 2015), were also reflected in public uncertainty about hydrogen safety, insurance risks, and economic viability.

Despite these parallels, the FCCP case offers three distinctive contributions to transition studies that have received limited attention so far. First, FCCPs illustrate that certain sustainability innovations require cross-sectoral alignment across multiple socio-technical regimes, in this case hydrogen production and distribution, cycling infrastructures, and urban logistics regulation. Their limited progress demonstrates how niches that cut across several regimes face a more complex alignment challenge than those situated within a single sector, extending debates on Strategic Niche Management that traditionally emphasize alignment within one socio-technical system (Geels, 2002; Schot and Geels, 2008).

Second, the findings showing that strong landscape pressures for clean mobility do not automatically translate into adoption. This adds empirical weight to critiques of the MLP for underplaying socio-cognitive dynamics, everyday practices and user learning within experimentation (Shove and Walker, 2010; Sovacool and Hess, 2023). By comparing ex-ante expectations with ex-post operational experiences, the analysis demonstrates how institutional visions of FCCPs were renegotiated once vehicles were deployed in practice, revealing a dynamic interplay between regime imaginaries and user perceptions.

Third, the FCCP pilots point to several recovery and reorientation pathways that could help revitalize a niche that has not yet demonstrated strong momentum. Adjustments driven by user feedback - such as improved ergonomics, simplified hydrogen modules, or value-adding features like cooling or heating of the cargo box - may enhance everyday usability and strengthen perceived relative advantage. Likewise, progress in standardizing small-vehicle hydrogen infrastructure and the use of public procurement as a strategic lever could help reduce complexity and increase compatibility with existing logistics routines. This aligns with emerging research on reorientation pathways, whereby underperforming niches can regain relevance through new coalitions or revised expectations (Kern et al., 2020; Turnheim and Geels, 2019).

Together, these insights refine current understandings of why some sustainability niches struggle to move beyond pilot phases, a critical issue for the early stages of socio-technical transition processes (Geels, 2024). The FCCP case shows how socio-institutional misalignments not only impede scaling, but also shape the possible routes through which niche innovations may be recalibrated and re-integrated into transition trajectories. This nuanced picture sets the stage for the conclusion, where the implications for urban logistics decarbonization and future FCCP development are summarized.

7 Conclusion, limitations, and future research directions

This study examined Fuel Cell Cargo Pedelecs as a cross-sectoral niche innovation situated between cycling, hydrogen mobility and urban logistics. Crucially, by comparing ex-ante expectations with ex-post operational experiences, the study shows how initial visions and expectations of FCCPs are often reinterpreted or challenged once vehicles are used in practice, revealing a dynamic relationship between regime imaginaries and user perceptions. While the pilots demonstrated that FCCPs can be operated reliably in specific delivery and service contexts, the empirical results show that they did not exhibit meaningful technical superiority over conventional electric cargo pedelecs. Across all three cities and some 15 use cases, daily delivery patterns remained well within the capabilities of battery-electric cargo bikes, meaning that the theoretical advantages of hydrogen, extended range and rapid refueling, were rarely needed in practice. Instead, the hydrogen system introduced additional layers of technical, organizational and regulatory complexity, including higher insurance costs, limited technician availability, specialized maintenance, and fragmented certification procedures. These constraints resulted in a situation where FCCPs were more demanding to operate while delivering no clear functional advantage in the observed logistics environments.

The dual-framework analysis combining the Multi-Level Perspective and diffusion theory reveals how these operational challenges interact with broader structural and behavioral factors. Landscape-level climate policies and hydrogen strategies created favorable expectations, yet this momentum did not translate into coherent support structures for small-scale hydrogen applications. At the regime level, urban logistics systems continue to favor established vehicle categories through existing maintenance ecosystems, regulatory procedures and procurement practices. These regime routines provide little institutional anchoring for hydrogen-based micro-mobility. Within the niche, pilot projects generated learning and visibility, but this learning has not yet stabilized into durable actor networks or market structures. User-level perceptions, shaped by concerns about safety, complexity and ergonomic constraints, further limited uptake and reduced trialability.

Taken together, the findings point to a constrained niche trajectory. FCCPs demonstrated operational feasibility and stimulated cross-sectoral collaboration, but they have not secured the institutional, infrastructural or market alignment necessary for broader diffusion. Their limited real-world advantage relative to simpler electric cargo bikes suggests that FCCPs will require more targeted operational niches, those that truly demand extended range or continuous operation, if hydrogen is to provide a distinctive value proposition. Without such niches, FCCPs risk remaining peripheral innovations dependent on project-based support rather than evolving into stable components of urban freight systems.

Advancing FCCP adoption will require coordinated efforts across policy development, infrastructure investment and logistics practice. Key priorities include harmonizing insurance and certification procedures, enabling micro scale hydrogen refueling solutions, strengthening cross city learning mechanisms and identifying use cases in which hydrogen propulsion provides a clear operational advantage over electric cargo bikes. Future research should analyze long term performance data, develop viable business models for hydrogen in light urban logistics and examine how governance arrangements shape the consolidation or stagnation of cross sectoral innovations. Beyond its empirical focus, this study contributes to transition research by demonstrating how cross-regime niche innovations face compounded alignment challenges not captured by studies focused on single-sector transitions.

This study has several limitations. First, it is based on a relatively small number of pilot implementations, limiting generalizability, as specific local conditions might not represent broader adoption scenarios. Second, although the MAMCA approach enabled structured stakeholder input, the limited number of participants, particularly from logistics providers, may influence policy measure prioritization. Third, the operationalization of Rogers' diffusion attributes was interpretive rather than quantitatively measured, which constrains the precision of adoption comparisons across user groups. Finally, the analysis captures FCCPs at an early stage of development, meaning the study reflects barriers to niche consolidation but cannot yet assess long-term market trajectories. By the same token, while the multi-site design supports analytical generalization of alignment dynamics, the findings remain context-dependent and should not be interpreted as predictive of FCCP diffusion outcomes in other urban or regulatory settings.

Future research could address these limitations by examining FCCP deployment across diverse cities, logistics contexts and regulatory environments, which would allow for stronger cross case generalization of the socio institutional alignment challenges identified here. Because our findings are based on three specific pilot contexts, broader comparative research is essential to assess whether similar patterns of niche fragility, regime misalignment and user level constraints appear elsewhere. Longitudinal studies could further trace how stakeholder perceptions evolve and how trialability and observability shape user mobilization over time, building on our finding that positive expectations alone do not guarantee diffusion. Comparative analyses between hydrogen and battery-electric cargo bikes may provide deeper insights into technology-specific lock-ins, extending debates on competing niche trajectories. Moreover, quantitative modeling of cost–benefit structures and infrastructure planning scenarios could support policymakers in integrating FCCPs within multimodal urban mobility systems. By explicitly linking cross-sectoral regime misalignments with user-level adoption attributes, future research can further refine the theoretical bridge we propose between transition studies and diffusion theory, advancing scholarship on constrained and recoverable niche pathways.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

LD: Writing – original draft, Writing – review & editing. DW: Conceptualization, Writing – review & editing. JG: Writing – original draft, Writing – review & editing.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Apostolou, D., Casero, P., Gil, V., and Xydis, G. (2021). Integration of a light mobility urban scale hydrogen refuelling station for cycling purposes in the transportation market. *Int. J. Hydrogen Energy* 46, 5756–5762. doi: 10.1016/j.ijhydene.2020.11.047

Cui, C., Liu, Y., Hope, A., and Wang, J. (2018). Review of studies on the Public–Private Partnerships (PPP) for infrastructure projects. *Int. J. Project Manag.* 36, 773–794. doi: 10.1016/j.ijproman.2018.03.004

Fichter, K., and Clausen, J. (2013). *Erfolg Und Scheitern 'Grüner' Innovationen: Warum Einige Nachhaltigkeitsinnovationen Am Markt Erfolgreich Sind Und Andere Nicht, 1st ed.* Berlin: Metropolis-Verl. German.

Fichter, K., and Clausen, J. (2016). Diffusion dynamics of sustainable innovation - insights on diffusion patterns based on the analysis of 100 sustainable product and service innovations. *J. Innov. Manag.* 4, 30–67. doi: 10.24840/2183-0606_004.002_0004

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Res. Policy* 31, 1257–1274. doi: 10.1016/S0048-7333(02)00062-8

Geels, F. W., and Ayoub, M. (2023). A socio-technical transition perspective on positive tipping points in climate change mitigation: analysing seven interacting feedback loops in offshore wind and electric vehicles acceleration. *Technol. Forecast. Soc. Change* 193:122639. doi: 10.1016/j.techfore.2023.122639

Geels, F. W., and Johnson, V. (2018). Towards a modular and temporal understanding of system diffusion: adoption models and socio-technical theories applied to Austrian biomass district-heating (1979–2013). *Energy Res. Soc. Sci.* 38, 138–153. doi: 10.1016/j.erss.2018.02.010

Geels, F. (2024). *Advanced Introduction To Sustainability Transitions. Edward Elgar*. Available online at: https://research.manchester.ac.uk/en/publications/advanced-introduction-to-sustainability-transitions/ (Accessed April 23, 2025).

Gernert, M., El Bilali, H., and Strassner, C. (2018). Grassroots initiatives as sustainability transition pioneers: implications and lessons for urban food systems. *Urban Sci.* 2:23. doi: 10.3390/urbansci2010023

Gibbs, D., and O'Neill, K. (2015). Building a green economy? Sustainability transitions in the UK building sector. *Geoforum* 59, 133–141. doi: 10.1016/j.geoforum.2014.12.004

Glover, K., Rudd, J. A., Jones, D. R., et al. (2021). The hydrogen bike: communicating the production and safety of green hydrogen. *Front. Commun.* 5:540635. doi: 10.3389/fcomm.2020.540635

Gruber, J., Rudolph, C., and Kolarova, V. (2015). Einflussfaktoren bei der Einführung des Lastenrads im urbanen Wirtschaftsverkehr. *ZFW Adv. Econ. Geogr. Z. Wirtschaftsgeogr.* 59, 115–129. German. doi: 10.1515/zfw.2015.0009

Harichandan, S., and Kar, S. K. (2023). An empirical study on consumer attitude and perception towards adoption of hydrogen fuel cell vehicles in India: policy implications for stakeholders. *Energy Policy* 178:113587. doi: 10.1016/j.enpol.2023.113587

Harichandan, S., Kar, S. K., Bansal, R., and Mishra, S. K. (2023). Achieving sustainable development goals through adoption of hydrogen fuel cell vehicles in India: an empirical analysis. *Int. J. Hydrogen Energy* 48, 4845–4859. doi: 10.1016/j.ijhydene.2022.11.024

Hillman, J., and Kirby, J. (2019). *The role of social enterprise in the transition to a low carbon energy system* (Doctoral dissertation). Liverpool John Moores University. Available online at: https://researchonline.ljmu.ac.uk/id/eprint/10081/

Jain, M. (2018). *Energy Transition In The Indian Building Sector: Assessing Net Zero Energy Buildings' Niche Development*. Enschede: University of Twente.

Karakaya, E., Hidalgo, A., and Nuur, C. (2015). Motivators for adoption of photovoltaic systems at grid parity: a case study from Southern Germany. *Renew. Sustain. Energy Rev.* 43, 1090–1098. doi: 10.1016/j.rser.2014.11.077

Kern, F., Sharp, H., and Hachmann, S. (2020). Governing the second deep transition towards a circular economy: how rules emerge, align and diffuse. *Environ. Innov. Soc. Transit.* 37, 171–186. doi: 10.1016/j.eist.2020.08.008

Kummer, K., and Imre, A. R. (2025). Supply of the hydrogen refuelling stations in the Hungarian part of the trans-european transport network – comparison of the methane splitting and water electrolysis. *Int. J. Hydrogen Energy* 186:152084. doi: 10.1016/j.ijhydene.2025.152084

Lee, Y., Kim, Y. J., and Lee, M. C. (2025). Navigating stakeholder perspectives on hydrogen generation technologies: a Q-methodology study of current hydrogen production policy in South Korea. *Int. J. Hydrogen Energy* 113, 777–786. doi: 10.1016/j.ijhydene.2025.02.431

Lilienthal, J. (2015). *Beeinflussungsfaktoren Der Diffusionsgeschwindigkeit Einer At-the-Bottom-Innovation In Einem Regionalen Bildungsnetzwerk* (Doctoral dissertation). Universität Oldenburg. German. Available online at: https://oops.uni-oldenburg.de/2498/

Liu, J., Chen, T., and Hu, B. (2023). Consumer acceptance under hydrogen energy promotion policy: evidence from Yangtze River Delta. *Int. J. Hydrogen Energy* 48, 11104–11112. doi: 10.1016/j.ijhydene.2022.07.081

Lodewyckx, S., Beasy, K., and Mattila, P. (2023). Pieces of a jigsaw: opportunities and challenges in the nascent Australian hydrogen mobility market. *Int. J. Hydrogen Energy* 48, 19821–19833. doi: 10.1016/j.ijhydene.2023.01.362

Lovell, H. (2007). The governance of innovation in socio-technical systems: the difficulties of strategic niche management in practice. *Sci. Public Policy* 34, 35–44. doi: 10.3152/030234207X190540

Macharis, C., Turcksin, L., and Lebeau, K. (2012). Multi actor multi criteria analysis (MAMCA) as a tool to support sustainable decisions: state of use. *Decis. Support Syst.* 54, 610–620. doi: 10.1016/j.dss.2012.08.008

Markard, J., Bento, N., Kittner, N., and Nuñez-Jimenez, A. (2020). Destined for decline? Examining nuclear energy from a technological innovation systems perspective. *Energy Res. Soc. Sci.* 67:101512. doi: 10.1016/j.erss.2020.101512

Martiskainen, M., Schot, J., and Sovacool, B. K. (2021). User innovation, niche construction and regime destabilization in heat pump transitions. *Environ. Innov. Soc. Transit.* 39, 119–140. doi: 10.1016/j.eist.2021.03.001

Nsamzinshuti, A., Ndiaye, A., Dablanc, L., and Gruber, J. (2022). *Multi-Actor Multi-Criteria Analysis (MAMCA) of the Integrated Policy Scenarios. Deliverable T3.5.2. Interreg North-West Europe*. Unpublished.

Pak, S. B., and Lee, Y. (2024). Common but differentiated? Policymakers' priorities of social acceptance for expanding hydrogen refueling stations in Japan and Korea. *Int. J. Hydrogen Energy* 89, 799–809. doi: 10.1016/j.ijhydene.2024.09.375

Rennings, K. (2000). Redefining innovation—eco-innovation research and the contribution from ecological economics. *Ecol. Econ.* 32, 319–332. doi: 10.1016/S0921-8009(99)00112-3

Rogers, E. M. (1983). *Diffusion of Innovations (3rd ed.).* New York, NY: Free Press [u.a.].

Sahin, I. (2006). Detailed review of Rogers' diffusion of innovations theory and educational technology-related studies based on Rogers' theory. *Turk. Online J. Educ. Technol. TOJET* 5, 14–23.

Schippl, J., Gudmundsson, H., Sørensen, C. H., et al. (2016). Different pathways for achieving cleaner urban areas: a roadmap towards the white paper goal for urban transport. *Transp. Res. Procedia* 14, 2604–2613. doi: 10.1016/j.trpro.2016.05.413

Schlund, D. (2023). *Integrating Cross-Border Hydrogen Infrastructure In European Natural Gas Networks: A Comprehensive Optimization Approach. EWI Working Paper 23/08*. Available online at: https://www.econstor.eu/handle/10419/286401

Schot, J., and Geels, F. W. (2008). Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy. *Technol. Anal. Strateg. Manage.* 20, 537–554. doi: 10.1080/09537320802292651

Shove, E., and Walker, G. (2010). Governing transitions in the sustainability of everyday life. *Res. Policy* 39, 471–476. doi: 10.1016/j.respol.2010.01.019

Smith, A., and Raven, R. (2012). What is protective space? Reconsidering niches in transitions to sustainability. *Res. Policy Spec. Sect. Sustain. Transit.* 41, 1025–1036. doi: 10.1016/j.respol.2011.12.012

Sovacool, B., and Hess, D. J. (2023). Ordering theories: typologies and conceptual frameworks for sociotechnical change. *Soc. Stud. Sci.* 47, 703–750. doi: 10.1177/0306312717709363

Turnheim, B., and Geels, F. W. (2019). Incumbent actors, guided search paths, and landmark projects in infra-system transitions: re-thinking strategic niche management with a case study of French tramway diffusion (1971–2016). *Res. Policy* 48, 1412–1428. doi: 10.1016/j.respol.2019.02.002

van Biert, L., Godjevac, M., Visser, K., and Aravind, P. V. (2016). A review of fuel cell systems for maritime applications. *J. Power Sources* 327, 345–364. doi: 10.1016/j.jpowsour.2016.07.007

Waes, A., van, Nikolaeva, A., and Raven, R. (2021). Challenges and dilemmas in strategic urban experimentation an analysis of four cycling innovation living labs. *Technol. Forecast. Soc. Change* 172:121004. doi: 10.1016/j.techfore.2021.121004

Zawieska, J., and Pieriegud, J. (2018). Smart city as a tool for sustainable mobility and transport decarbonisation. *Transp. Policy* 63, 39–50. doi: 10.1016/j.tranpol.2017.11.004

 10.3389/frsc.2025.1701390

Appendix

Results of the Multi-Actor Multi-Criteria Analysis (MAMCA) ranking for 18 policy measures supporting FCCP adoption (Nsamzinshuti et al., 2022). The table reports aggregated priority scores from the ex-ante evaluation, derived from stakeholder preferences across the assessment criteria (cost–benefit relation, relevance, implementation timescale, political acceptance). Scores reflect inputs from logistics operators and municipal representatives ($n = 33$). Higher values correspond to measures perceived as more important or more impactful for facilitating FCCP deployment.

TABLE A1 Results of the MAMCA.

Dimensions	Policy measures	Logistics operators	Cities
Urban planning measures	Municipality operates micro depot (e.g., landlord model)	2.30	2.32
	Municipality gives public space to logistics service providers at subsidized conditions	2.12	2.14
	Building construction considers areas for logistics operations (e.g., loading bays, parcel lockers)	2.36	2.43
Pricing and regulatory measures	Subsidizing commercially used cargo cycles	2.75	2.78
	Public funding of scientific or commercial cargo bike projects	2.81	2.84
	Restriction of motorized private and delivery vehicle use (e.g., reduced speed limit, increased parking fees, restricted delivery time, city toll, low emission zone, circulation plan)	4.50	4.58
Infrastructural measures	Building a new network of high quality bicycle infrastructure	4.56	4.63
	Implement cargo bike parking facilities	3.50	3.55
	Bicycle speed ways	3.49	3.51
Measures to promote cargo bikes	Campaign for cargo bikes	3.56	3.60
	Initiate cargo bike testing programs	3.93	4.02
	Use cargo bikes in municipal deliveries	3.92	3.98
	Integrate cargo bikes in bike sharing schemes	3.01	2.99
Specific measures in respect to hydrogen as an energy source	Development of a coherent hydrogen fuel station network for a city	4.31	4.37
	Facilitate/moderate a dialogue with stakeholders to install hydrogen stations	4.06	4.11
	Public relations/Information campaigns/knowledge transfer	4.06	4.12
	Training sessions	3.43	3.43
	Local funding program for hydrogen infrastructure	3.69	3.72

(Continued)

TABLE A1 (Continued)