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Fueling Tomorrow: Scenario Planning for the Future of Gas Stations

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ABSTRACT

Transport electrification is reshaping the service infrastructures that mediate everyday mobility, yet most electrification scenario studies remain macrolevel and offer limited insight into how incumbent forecourt (gas-station) networks can adapt under deep uncertainty. This study recenters gas stations as sociotechnical transition actors and develops a traceable, design-integrated scenario approach to derive place-based transition pathways. Using a Canadian case (with emphasis on Quebec), we combine field observation and hierarchical task analysis with a PESTEL horizon scan (patents, literature, and policy) and a two-round Delphi with nine experts. A QFD-inspired impact matrix and expert appraisal are used to construct and validate 12 prospective service-use scenarios across urban, highway, and rural/outskirt contexts. Results indicate three recurring pathway archetypes: (1) urban charging embedded in commercial/parking ecosystems, (2) highway destination-style multi-service hubs requiring high-CAPEX energy and service orchestration, and (3) rural/outskirt nodes where on-site generation and prosumer participation plausibly complement conventional station roles. Across scenarios, feasibility is shaped by permitting and interconnection timelines, grid capacity constraints, land-use and safety requirements, user acceptance, and utilization-sensitive economics. The scenario set yields capability and staging logics that support policy-industry coordination and roadmapping/portfolio decisions during prolonged coexistence of liquid-fuel and electric infrastructures.

1 | Introduction

The world is grappling with an escalating environmental crisis, marked by rising greenhouse-gas emissions and their detrimental effects on ecosystems and human health. In response, nations are adopting strategies to mitigate emissions in line with the Paris Agreement's goal of limiting global temperature rise to below 2°C above pre-industrial levels (Erikson and Brase 2019). Among these strategies, transport electrification has emerged as a pivotal approach for decarbonizing mobility, transforming transportation systems while requiring new infrastructures and service models to support electric-vehicle (EV) adoption (Bogdanov et al. 2024; Gribkova and Milshina 2022).

Like every major technological transition, electrification introduces profound uncertainty about markets, regulation, technologies, and user practices. Such uncertainty complicates strategic decisions for public and private actors and motivates the use of foresight approaches. Scenario planning supports strategic thinking by exploring multiple plausible futures, enabling learning, sensemaking, and robust decision-making under uncertainty rather than attempting precise prediction

The study acknowledges the inherent chaos in scenario creation (Spaniol and Rowland 2019), aligning with the theoretical debates on the subject. It highlights the importance of flexible strategies, emphasizing responsiveness to change over rigid prediction (van der Heijden 2011). The influence of Godet's (2000) perspective on collective thinking and the art of scenario creation is evident in the process. The call for interdisciplinary perspectives and creativity, prevalent in both the theoretical background and approach application, is a resonating theme. The approach stresses the collaboration of practitioners, users, and experts in shaping scenarios, mirroring the importance assigned to collective thinking and nonconformism in the theoretical discourse.

(Godet 2000; Chermack 2005; Voros 2006; van der Duin and van der Steen 2012; Hussain et al. 2017).

In the context of energy and mobility transitions, forecasting challenges are amplified by interacting uncertainties (e.g., adoption dynamics, infrastructure constraints, supply chains, and technological change) making it difficult to develop flexible strategies that remain viable across a range of futures (Kost et al. 2021; Jochem et al. 2024; Du 2024; Hua et al. 2025; Wang et al. 2025). Even if electrification progresses as planned, the coexistence of gasoline and electric infrastructures is likely to persist for many years. This coexistence underscores the strategic importance of adapting incumbent infrastructures (such as gas stations) so they remain functional and potentially valuable during the transition (Sun et al. 2024).

While the literature is prolific in proposing scenario-planning tools for strategic decision-making, recent work on transport electrification is predominantly macro-oriented and often directed toward public planning (e.g., Wang et al. 2024; Sun et al. 2024). At the same time, prospective scenarios are widely considered important for supporting decisions, yet practical guidance on how to create, validate, and use such scenarios (especially in design- and operations-relevant ways) remains limited (Spaniol and Rowland 2019). More broadly, foresight is increasingly important for innovation in markets that do not yet exist, but the literature provides limited procedural clarity on how to source inputs, structure uncertainty, and integrate multiple perspectives into prospective scenarios (Bruseberg and McDonagh-Philp 2001; Kahn 2012; Wolf et al. 2018).

Moreover, comparatively little attention is given to how incumbent service infrastructures within the mobility ecosystem translate external uncertainties into actionable service-system pathways. Existing electrification scenario studies largely operate at the macrosystem level (policy uptake, infrastructure totals), leaving a gap in how incumbent service infrastructures translate external uncertainties into actionable service-system pathways (LaMonaca and Ryan 2022). This gap limits scholarly understanding of incumbent adaptation mechanisms and constrains how firms and policymakers stage investments under uncertainty.

This study contributes primarily to sustainable mobility transition research by theorizing the forecourt (gas-station) network as an underexamined incumbent service infrastructure within the mobility ecosystem. Rather than assuming a uniform "station-to-charger conversion," we show that electrification plausibly generates spatially differentiated transition pathways (urban, highway, and rural/outskirt) whose viability depends on trip purpose, dwell-time economics, land-use constraints, grid interaction, and long periods of multi-infrastructure coexistence. This reframes the academic question from whether gas stations "survive" electrification to how incumbent service infrastructures recombine services, coordination roles, and capabilities under deep uncertainty.

Second, to surface these pathway mechanisms rigorously, we provide a traceable scenario-design procedure that links task-level service analysis with multidomain horizon scanning (PESTEL) and structured impact synthesis. Third, we derive capability and staging logic that informs infrastructure strategies (e.g., sequencing, roadmapping, and portfolio decisions) when legacy and emerging systems must coexist for extended periods. We therefore pose the following research questions:

Research Question 1. How can a traceable scenario-creation approach be constructed for far-future service systems under electrification uncertainty?

Research Question 2. What differentiated pathways emerge for gas stations across contexts, and what capabilities do they imply?

Although empirically anchored in gas stations, the theoretical lens (incumbent service infrastructures as transition actors) and the traceable scenario-design procedure are transferable to other mobility intermediaries (e.g., parking operators, repair networks, and logistics depots) facing deep uncertainty during electrification.

The remainder of this paper is structured as follows: Chapter 2 presents the theoretical background, Chapter 3 details the methodology, Chapter 4 reports the results, and Chapter 5 provides the discussion. Finally, the conclusion highlights limitations and directions for future research.

2 | Theoretical Background

In this paper, forecasting refers to probabilistic or model-based estimation of future states; strategic planning refers to selecting actions and allocating resources toward objectives; foresight refers to systematic exploration of possible futures to enhance preparedness and learning; and scenario planning refers to constructing a small set of internally consistent future situations to support sensemaking and robust strategy rather than prediction.

2.1 | The Future of Mobility

The mobility transition is not linear. It is a contested, multitechnology pathway with open questions regarding energy carriers, long-distance segments, battery trajectories, automation, and "smart" system integration. While battery-electric propulsion currently dominates light-duty pathways, scholars emphasize interactions with electric grids and other critical infrastructures, as well as alternative vectors (e.g., hydrogen and e-fuels) whose competitiveness depends on infrastructure readiness, costs, and policy design (Torkey et al. 2024).

Long-distance travel remains difficult to decarbonize. Expert assessments point to a persistent role for energy-dense liquid fuels in long-haul road freight and other long-distance modes in the medium term, implying heterogeneous transition speeds across segments (U.S. Environmental Protection Agency (MSTRS) 2021). At the same time, battery lifespan, degradation under varied usage and charging patterns, raw-material constraints, and future chemistry evolution remain sources of strategic uncertainty for firms planning products and infrastructure (MIT Energy Initiative 2019).

Autonomy and digital platforms may reshape travel demand, charging behavior, and asset utilization, but their timing and magnitude are uncertain—reinforcing the relevance of scenario-oriented approaches under deep uncertainty (Amer et al. 2013). Additional uncertainties include spatial and social inequities, the home-versus-public charging split, and the role of ultra-rapid public hubs for drivers without home charging (Dorsey et al. 2022; Hopkins et al. 2023). These uncertainties affect business models and challenge legacy refueling strategies. Moreover, costs, charging speeds, and user behavior introduce parameter uncertainty that shapes EV diffusion[1] and associated energy impacts, strengthening the case for strategy tools that explicitly account for uncertainty (Niu et al. 2024).

The gas station (forecourt) actor remains underexplored. Although literature often emphasizes vehicles, the power system, and public policy, the role of fuel stations/forecourts as charging and service nodes is comparatively underexamined. Yet this is a capital-intensive sector characterized by long asset lifetimes (often multiple decades), high construction and operational costs, and intensified competition as new technologies and entrants emerge (Alves Ribeiro Rosa et al. 2021). As a result, gas stations face complex and uncertain decisions about service redesign and business-model reconfiguration across transition periods and longer horizons.

Recent work has begun to address the transformation of stations into charging hubs and to map how regulators, investors, and users co-evolve in this redesign (Sun et al. 2024; Arup 2024). Large operators (e.g., Shell) are already signaling conversion strategies and rapid-charging expansion across existing networks. However, these developments remain thinly theorized in terms of business models, service formats, and urban integration. By centering the gas-station actor, this research addresses a blind spot: how service-station ecosystems (convenience retail, food, and energy services) connect to future use scenarios, grid infrastructure, and technology choices prior to portfolio decisions.

More specifically, three gaps persist. Conceptually, refueling/forecourt networks are often treated as passive "sites" within charging deployment, rather than as incumbent service infrastructures that actively reconfigure services, roles, and capabilities during sociotechnical transitions. Empirically, the literature above provides limited clarity on how incumbent adaptation differs across place-based contexts (urban, highway, and rural/outskirt) where trip purpose, dwell-time, land-use constraints, and grid interactions fundamentally alter viable service and investment logics. Methodologically, while electrification scenarios are abundant at the macro level (uptake rates and infrastructure totals), fewer studies provide an end-to-end, traceable procedure that translates such uncertainties into design- and operations-relevant scenarios and capability requirements for incumbent actors (Dorsey et al. 2022; Hopkins et al. 2023).

Addressing these gaps matters because forecourts are widely distributed nodes that may shape the pace and equity of electrification, particularly for drivers relying on public charging. Thus, clearer pathway understanding can improve the staging of investments and public-private coordination under prolonged infrastructure coexistence.

2.2 | Strategic Tools in the Fuzzy Front End

The front end of new product development (NPD), often termed the "fuzzy front end" (FFE), precedes formal concept approval and encompasses opportunity identification, problem/need framing, and early concept shaping under strategic constraints (product/market/technology) (Koen et al. 2001; Oliveira and Rozenfeld 2010; Crawford and Di Benedetto 2011). In this stage, organizations screen emergent market needs and technological possibilities, translate them into product concepts, and decide which project(s) to pursue (activities that are inherently uncertain and information-poor) (Reid and de Brentani 2004; Oliveira and Rozenfeld 2010). Accordingly, this is typically where prospective and foresight-oriented strategic tools are mobilized.

Technology roadmapping (TRM) is a flexible and visual framework that links markets, products, and technologies across time to support long-range planning and cross-functional alignment (Phaal et al. 2004). Typical outputs synchronize "where we are," "where we are going," and "how to get there," positioning TRM as a preportfolio, preproject device rather than a project list (Kappel 2001; Phaal et al. 2004). Organizations adopt TRM under conditions such as looming market shifts, industry-level challenges, or the need to align with policy priorities. A recurring challenge is adapting roadmaps to different contexts and maturities and integrating them with complementary foresight methods (Kappel 2001; de Alcantara and Martens 2019). Recent reviews map TRM "models," their steps, and embedded tools, reinforcing TRM's role as a scaffold for strategic alignment rather than an answer (de Alcantara and Martens 2019).

Product/Project Portfolio Management (PPM) selects and prioritizes development investments to maximize value, balance risk, and ensure strategic fit (Cooper et al. 2001; Gupta et al. 2022). While indispensable downstream, PPM requires forward-looking inputs—namely, a rich funnel of future-oriented options and concepts—which the FFE must supply. Consequently, PPM and TRM are complementary. TRM articulates strategic pathways and technology/market timing, while PPM operationalizes choices among candidate projects consistent with those pathways (Cooper et al. 2001; Phaal et al. 2004). Both therefore depend on strategic, creative, and multidimensional inputs, motivating scenario-based approaches that can structure uncertainty and expand the space of plausible future options.

In this paper, prospective scenarios are treated as a structured upstream input to these tools, enabling traceable reasoning from uncertain external conditions to capability pathways and portfolio-relevant options.

2.3 | Scenario Planning for Far-Future

2.3.1 | Scenario Planning Under Deep Uncertainty

Imagining how trends may unfold is not new. Scenario approaches emerged in defense contexts and later diffused into industry and management as tools for thinking and acting under uncertainty (Bradfield et al. 2005). Across disciplines, a "scenario" broadly denotes a representation of a situation (past, present, or future) used to support reasoning and decision-making

(Chermack 2005; Rasmussen et al. 2010). In this paper, we focus on prospective scenarios, i.e., future-oriented projections represented through internally coherent situations rather than predictions (Oliveira and Rozenfeld 2010).

In strategic management and the social sciences, scenario planning explores multiple plausible futures to challenge assumptions and support resilient strategies in uncertain environments (Godet 2000; van der Heijden 2011). Beyond macro-level policymaking, scenarios are increasingly used within firms to improve strategic conversation, reduce cognitive bias, and enhance decision quality (Meissner and Wulf 2013; Lehr et al. 2017). Methodologically, reviews emphasize that scenario robustness benefits from combining qualitative logics with structured techniques (e.g., cross-impact, morphological analysis), particularly when futures depend on multiple interacting uncertainties (Amer et al. 2013). This is especially salient for front-end innovation, where forward-looking inputs must remain flexible and decision-relevant (Hussain et al. 2017).

A recurrent finding is that no single tool suffices for the FFE. Integration is key for sourcing inputs, structuring uncertainty, and translating futures into actionable options (Hussain et al. 2017). Scenario outputs can also feed other strategic management tools by providing future-ready options and by enabling rolling reassessments as conditions evolve. Recent work reframes portfolio decision-making as a dynamic capability, strengthening the case for scenario-informed and adaptable portfolios in turbulent contexts (Gupta et al. 2022). However, despite extensive conceptual development, practical guidance on how to create, validate, and use far-future scenarios in a traceable manner remains limited, particularly when scenarios are intended to inform concrete design and operational choices.

Validation remains a persistent challenge because prospective scenarios cannot be "ultimately" verified by observing whether they occur. Comparative reviews therefore propose evaluative criteria such as plausibility, internal consistency, relevance, novelty/creativity, and differentiation (Wilson 1998; van der Heijden 2011; Amer et al. 2013). Wilson's (1998) set (i.e., plausibility, consistency, relevance, and differentiation) remains a widely used yardstick in management settings and motivates the expert-based appraisal stage adopted in this study.

2.3.2 | Scenarios in Design and NPD

In design and NDP, scenarios have been developed as practical artifacts to support creativity, ideation, and evaluation by describing how agents pursue goals through sequences of actions in context (Rosson and Carroll 2007; Nelson 2011; Weidenhaupt et al. 1998). Scenario parameters typically include an agent, objectives, a flow of actions, and a situated context that captures constraints and interactions at a given time (Weidenhaupt et al. 1998; Rosson and Carroll 2007; Nelson 2011). Scenarios may take the form of narratives, presentations, or verbal exchanges, and may be complemented by visual or audiovisual resources (Achour 1999; Kankainen et al. 2012). They are informed by empirical data on key drivers and interactions as well as by the knowledge and experience of those constructing them (Schmidt-Scheele 2020).

A variety of scenario types exist in design practice. For the purposes of this research, usage-oriented scenarios are particularly relevant because they translate future conditions into concrete service interactions and capability requirements, supporting concept generation and early evaluation in the FFE (Fulton Suri and Marsh 2000; Rosson and Carroll 2007; Lallemand and Gronier 2018). Scenario-based approaches have been used both to critique current practices (problem scenarios) and to articulate proposed future solutions (design scenarios), and they are often integrated with creativity methods and stakeholder knowledge to expand the space of plausible concepts (Rosson et al. 2002; Nelson et al. 2014; Moon and Han 2016; Brangier et al. 2019). This design orientation is particularly important for far-future foresight because it helps bridge abstract trend extrapolations and the concrete operational implications that organizations must consider when making early-stage strategic and portfolio decisions.

2.4 | Synthesis and Research Gap

Given the complexities outlined above, strategic discussion and planning remain necessary. Prior quantitative and policy-oriented streams examine how incentives, infrastructure availability, and information conditions shape EV uptake and charging deployment (Knittel and Tanaka 2025). However, these streams rarely translate such drivers into design- and operations-level capability requirements for incumbent forecourt networks, nor do they provide an end-to-end procedure for generating and validating differentiated use scenarios for such actors (Sun et al. 2024; Sabyasachi et al. 2024; Zhang et al. 2024; IEA 2025; Natural Resources Canada 2024). Complementary work (particularly in Energy Policy) analyzes network reconfiguration and stakeholder coordination, while practice-oriented reports discuss conversion typologies and urban implications (Sun et al. 2024; Arup 2024). In parallel, operator strategy documents[2] increasingly signal site closures/conversions and the expansion of rapid-charging networks, highlighting the immediacy of these decisions.

Recent modeling studies also combine innovation incentives, information/education mechanisms, and retail coordination to explore how multi-actor interventions affect EV-ecosystem outcomes, offering insights relevant to investment timing and coordination choices (Wang et al. 2024). At the technology level, empirical and review work documents steep historical declines in lithium-ion battery costs while highlighting variance across chemistries, supply chains, and learning rates. Factors that shape total cost of ownership assumptions in scenarios (Nykvist and Nilsson 2015). Diffusion studies further show that adoption depends on heterogeneous users, policy incentives, charging availability, and model variety, suggesting that scenario ensembles should vary these parameters explicitly rather than relying on single-point forecasts (Gnann and Plötz 2015).

At the system level, transport scenarios within integrated assessment models examine how electrification, efficiency, and modal shifts may meet climate targets under different socioeconomic pathways (McCollum et al. 2012; Riahi et al. 2017). Collectively, these global scenarios underscore that mobility outcomes hinge on broader assumptions about urban form, energy mixes, and policy ambition. Yet they leave a gap in understanding how these macro uncertainties translate into actionable service-system pathways for incumbent infrastructures such as forecourts. Addressing these conceptual, empirical, and methodological gaps motivates the present study's traceable, design-integrated approach to creating and validating far-future use scenarios for gas stations.

3 | Methods

To address Research Question 1 (constructing a traceable scenario-creation approach for far-future service systems under electrification uncertainty) and Research Question 2 (identifying differentiated pathways and implied capabilities across contexts), we adopted Design Research Methodology (DRM) as an overarching research design (Blessing and Chakrabarti 2009; Hevner and Chatterjee 2010). DRM is appropriate because the study's core output is an artifact (a set of structured, evidence-traceable scenarios) developed iteratively through (i) problem/system understanding, (ii) artifact construction, and (iii) stakeholder-based evaluation.

We applied the approach to gas stations in Quebec, Canada, and structured environmental scanning using PESTEL to ensure multidomain coverage of external uncertainties. Ethics approval was obtained, and data protection procedures were followed.

Quebec provides a relevant empirical setting because it combines a strong policy push toward transport decarbonization, a distinctive electricity/energy context relative to many jurisdictions, and a mix of dense urban areas, long-distance corridors, and rural/outskirt territories. This supports scenario differentiation by location and trip purpose. The case is used to develop transferable method logic (traceable scenario creation), while recognizing that scenario content may vary under different regulatory and infrastructure regimes.

Table 1 summarizes the study steps.

3.1 | System Variables Exploration

To conduct a structural analysis of the gas-station system, its actors and services, we used field observations (Kawulich 2005; Ciesielska et al. 2018) and hierarchical task analysis (HTA) (Annett 2003; Phipps et al. 2011). Field observations identified actors, actions, and relationships in situ. We developed two HTAs (one for workers and one for users), covering payment at the pump and payment at the cash register. We defined the goals of both actors, mapped task-level interactions, and identified aspects likely to change. Components were then analyzed across hierarchical levels, focusing on elements influenced by external factors.

From this, we identified key system elements ("system variables") anchored in stakeholders' needs and goals. These variables guided subsequent data collection. We then applied morphological analysis to break down future-related factors into dimensions (Durance and Godet 2010) and organized data using the PESTEL framework as support for collection and analysis.

3.2 | Future Conditions Analysis

We sought strong and weak signals across PESTEL dimensions using the following data sources.

3.2.1 | Patents

Searches in Canadian Intellectual Property Office (CIPO), United States Patent and Trademark Office (USPTO—PatFT/AppFT), and World Intellectual Property Organization (WIPO—PATENTSCOPE), starting with broad terms ("vehicle," "gas

TABLE 1 | Methodological structure of the study.

Phases	Activities	Methods	Outcomes
(1) System variables exploration	Understand the system; select variables.	Field observation; Hierarchical Task Analysis (HTA); task-level mapping of worker/user interactions.	System variables
(2) Future conditions analysis	Identify and classify future conditions (strong/weak signals) across PESTEL framework.	Patent database searches with text mining; academic literature; documentation review (prospective studies, media, agendas, international agreements, statistical agencies, trend and regulatory/government reports); Interviews (Delphi).	Future conditions
(3) Data synthesis and interpretation	Analyze and confront data; make sense of relationships and impacts.	Impact matrices; elements of disruption; intuitive logic.	Basis for scenarios
(4) Scenario crafting and storytelling	Define scenario parameters; generate diverse scenarios; develop narratives.	Brainstorming; General Morphological Analysis (GMA); creativity/ideation with programmatic random combinations.	Scenarios
(5) Validation	Confront literature-derived criteria; evaluate scenarios.	Criteria evaluation; Interviews (Delphi); expert voting.	Validation

station") and narrowing to "vehicle and energy," "vehicle and battery," "energy generation/generator," and "energy and gas station." Text mining (R Core Team 2024) complemented relevance/recency screening to identify trends and technological possibilities.

3.2.2 | Academic Literature

Initial Web of Science searches ("gas station" and "vehicle") across relevant fields. Results were exported to software VOSviewer (Waltman et al. 2010; Perianes-Rodríguez et al. 2016) for bibliometric mapping and text mining, revealing authors, journals, frequent terms, and clustered themes. Two additional searches were analyzed with VOSviewer and screened by titles/abstracts: ("service station" OR "gas station") AND ("future" OR "prospect*" OR "improvement" OR "development" OR "chang*" OR "enhanc*").

3.2.3 | Other Documentation

Prior prospective studies (e.g., Bezdek and Wendling 2002), media, political agendas and international agreements, statistical data (Statistics Canada, Statistics Quebec, World Health Organization-WHO, Organisation for Economic Co-operation and Development-OECD, United Nations-UN, World Bank), trend reports (e.g., Gartner, Klynveld Peat Marwick Goerdeler-KPMG, World Bank Group, International Energy Agency-IEA), and regulatory/government sources (Canada Energy Regulator, Quebec Energy Regulator, ministry reports).

3.2.4 | Delphi Interviews

Semi-structured interviews with nine experts took place twice. Expert domains were derived from Porter's Five Forces (Porter 1980) to reflect system actors (competitors, clients, suppliers, new entrants, substitutes). They had > 10 years of experience while relevant degrees and diversity of perspectives were prioritized. Interviews (≈1 h each) covered drivers and barriers for service stations' futures and trend categories (technological, political, social, demographic, etc.). Transcripts were coded in TAMS Analyzer software into trends, constraints, and visions of the future. Trends were subdivided (energy, socioeconomic, technological, and vehicle) and constraints were subdivided (environmental and socioeconomic, technological). Text mining identified the most-cited terms and co-occurrences. Then, the second interview took place for validation of the scenarios generated following the criteria described in item 3.5. Finally, prospective data were classified to reduce complexity: trends and constraints (both mappable to PESTEL) and visions of the future (reserved for scenario creation). As for factor behavior, they were categorized as negative/refusal/downward, neutral/indeterminate/stable, or positive/acceptance/upward to aid impact assessment.

3.2.5 | Experts Profiles (E1–E9)

Industrial-plan economist (E1); interface-futures designer (E2); IoT/data science expert (E3); oil-company retail operations director and former station manager (E4); innovation/projects leader in a competing oil company (E5); former strategic development head in an energy supply company and creativity professor (E6); strategy consultant in an energy company (E7); senior researcher in transport/logistics (E8); professor in modularization, energy conversion, and distribution (E9). All are > 30 years old with > 10 years' experience; one DEC/bachelor's (E5), seven master's, and one PhD (E9).

The Delphi panel was purposively composed to maximize perspective diversity across the service-station ecosystem (retail operations, competing incumbents, energy systems, mobility/logistics, digital/IoT, and futures/design), rather than to estimate population parameters. Delphi panel sizes vary widely, but reviews report that panels most commonly fall in the 8–20 range given feasibility constraints (Hsu and Sandford 2007; Shang 2023). Given the study objective (i.e., eliciting drivers, constraints, and bounded plausibility judgments for scenario validation) depth of expertise and coverage of key actor perspectives were prioritized over sample size. Two rounds were used to separate elicitation (drivers/constraints/visions) from appraisal (scenario validation) and to reduce single-interview volatility.

3.3 | Data Synthesis and Interpretation

To relate variables (system) and conditionals (future), we built a system variables × future conditions matrix inspired by Quality Function Deployment (QFD). The QFD is a decision support tool that represents aspects that are critical for the customer (Cheng 2002). This method seeks to convert customer opinions into engineering specifications and thus, into production (Cheng 2002). QFD also aims to prioritize the customer by assigning values or weights to elements in the matrix.

We assigned weights to each relationship: 1 (strong/direct), 0.5 (moderate/indirect), 0 (no significant impact). Row/column sums were color-coded: > 10 (yellow), > 20 (orange), > 30 (red). This highlighted disturbance elements (future conditions) and the most impacted variables, supporting multi-level projections (from discrete events affecting products/functions up to system-level impacts).

All data were synthesized into a QFD matrix, integrated in text summaries and accompanying graphs. The research group then convened a series of meetings to discuss the overall results and to conduct their analysis, structure, and interpretation.

3.4 | Scenario Crafting and Storytelling

Design scenarios were structured around a user performing an activity in a future environment using artifacts. We grouped artifacts into technology/interface and vehicle, and the environment into energy and context. Scenario parameters included: (1) activity/need (e.g., recharging), (2) stakeholder/user (e.g., family with children), (3) energy type (e.g., hydroelectricity), (4) vehicle type (e.g., flying car), (5) context/location (urban, countryside, roads/highways), and (6) technology/interface (e.g., induction charging).

We populated parameter values from the research, then used brainstorming (Al-Samarraie and Hurmuzan 2018) and General Morphological Analysis (GMA) (Zwicky 1969; Ritchey 2011) with programmatic random combinations to generate diverse configurations. The GMA takes the parameters and their values and explores possible relationships that can be used to structure different scenarios.

We ran random combinations and from these results created a scenario for each. Resulting structures were elaborated into storylines that referenced the underlying trends and constraints; brainstorming informed narrative refinement. Scenarios were considered "robust enough" once activities and key interaction elements were fully visualizable.

3.5 | Validation

Validation combined criteria attributed to Wilson (1998) and van der Heijden (2011) (five total, counting novelty and original perspectives together):

> *Consistency*: Ensured by grounding scenarios in the collected data and methods, then confirmed via expert "makes sense/consistent" votes.
>
> *Differentiation*: Similar scenarios were clustered; representatives were scored and selected to ensure heterogeneity and to reflect uncertainties (at least two uncertain/disruptive scenarios).
>
> *Plausibility*: Stakeholders/experts scored plausibility individually (out-loud voting).
>
> *Relevance* and *Novelty/Original perspectives*: Assessed for usefulness.

For each location cluster (urban, highway, rural/outskirt), experts ranked the three most plausible scenarios, assigning scores of 3, 2, and 1 respectively. Scores were aggregated across experts to obtain relative plausibility ordering within each cluster. Experts also identified, within each cluster, the scenarios they considered nearest-term and farthest-term; these judgments were aggregated to position scenarios along a time-horizon axis. The resulting plausibility–time mapping supports discussion of staging and prioritization (near-, mid-, and long-horizon exploration). Therefore, near-term means ~0–5 years, mid-term: ~5–15 and far-term: ~15 + .

4 | Results

4.1 | Systems Variables

Understanding the system requires more than listing parts. It demands grasping interrelationships and core functions within the gas station's domain. Variables tied to stakeholder needs and system goals guided data exploration and revealed how the system evolves over time.

The temporal scope covered 5–10 years (short term) and 20+ years (long term). The analytical boundaries focused on stakeholders who directly interact with or influence the system (e.g., owners, employees, customers, suppliers, government, and community). Activities included cashier operations during fuel and product sales and user/customer actions on the station premises. For users, the analysis included in-station actions, interactions with products and technologies (vehicle, fuel/energy), routes to the station, and external trip factors (traffic, location, and weather). For workers, it covers actions, product/technology interactions, and functions that ensure safety and operational efficiency. This method selection prioritized applicability to Canadian service stations.

Field observations and HTA (Kawulich 2005; Ciesielska et al. 2018) facilitated a nuanced understanding of workplace dynamics, activities, interfaces, and user interactions. These methods provided a systemic view of variables, their hierarchical importance, and domains for prospective data collection. Relationships among stakeholders (suppliers, customers, cashiers, managers, and owners) are complex and interdependent, supporting effective and profitable operations.

To understand needs and anticipate future iterations, we identified 41 variables for prospecting, cross-analysis, and impact assessment, categorized into stakeholder needs, user-experience aspects, security, energy, vehicle type, and system functions. Of these, 11 mapped to stakeholder needs; 13 to user-experience aspects; 8 to security; 4 to energy; 3 to vehicle type; and 2 to system functions. No new variables were added after the exercise, though some were merged when they described facets of the same variable.

4.2 | Future Conditions

Linking system variables to conditions of the future produced projections of change (or stagnation) at multiple levels, from discrete events that affect products and functions to transformations at the system level. From over two hundred identified trends and constraints, we filtered to approximately one hundred, based on disparities in their relationships to selected variables.

Structuring data aided sense-making without constraining creativity . Analyses necessarily considered weak correlations (today's slight indications can become tomorrow's trends). Technological applications were hard to foresee, so multidisciplinary expertise helped interpret impacts on systems and interfaces.

4.2.1 | Literature Review

For the literature corpus (Snyder 2019; Donthu et al. 2021), text mining supported author/journal mapping and theme clustering. Figures 1 and 2 illustrate word co-occurrence network visualizations generated using the VOSviewer software. Clustering focused on the most frequently quoted words in articles related to energy futures (Figure 1) and the future of service stations (Figure 2). In these visualizations, each node represents a

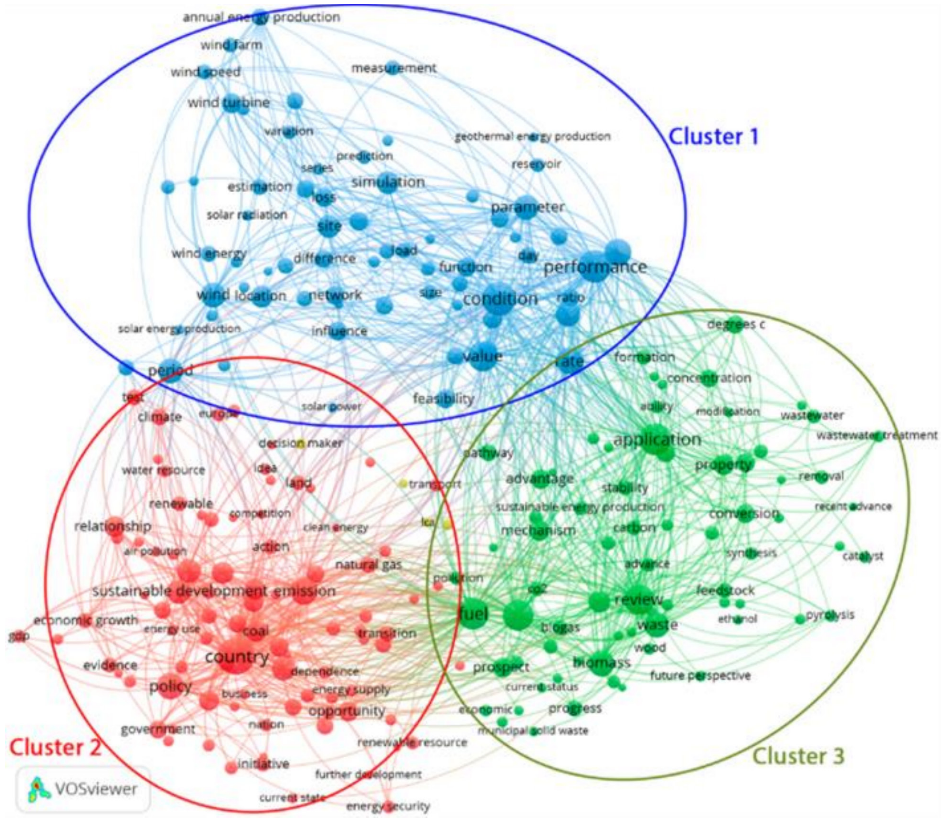

FIGURE 1 | Clusters derived from the literature on the future of energy (VOSviewer).

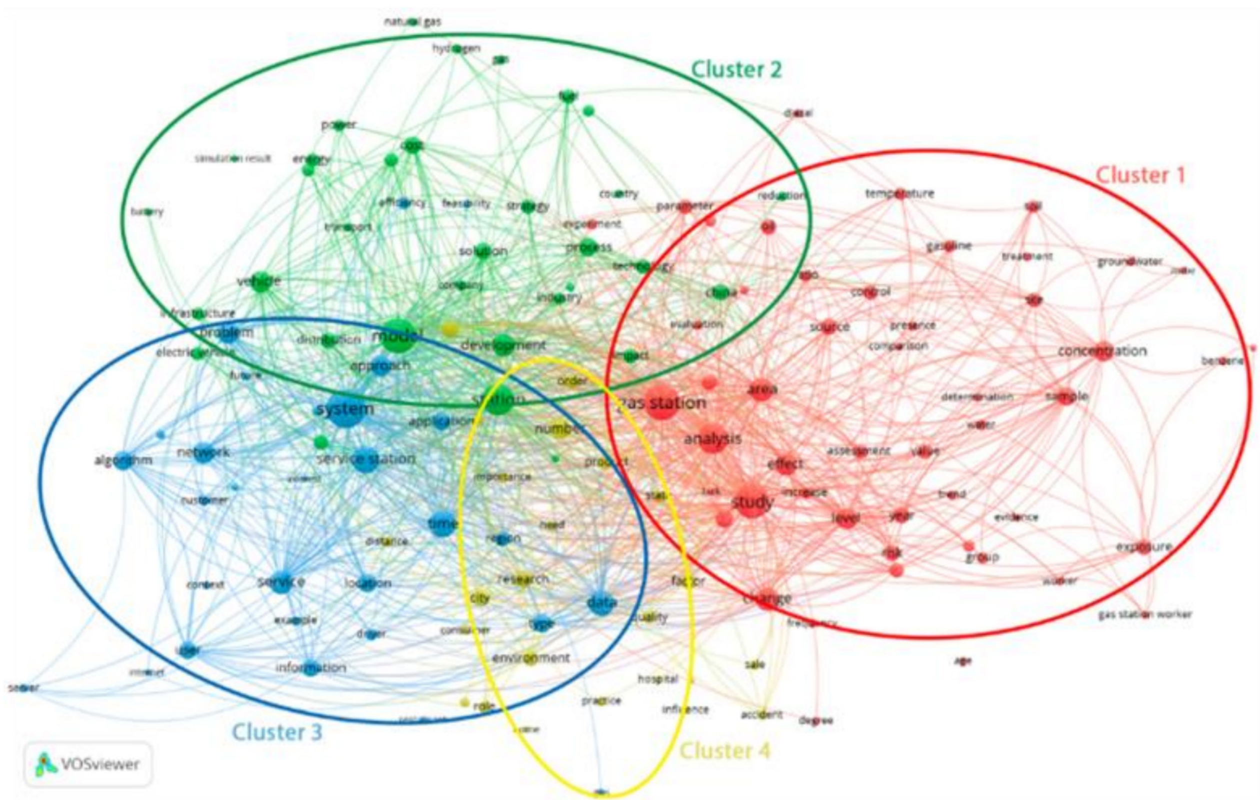

FIGURE 2 | Clusters derived from the literature on the future of service stations (VOSviewer).

word, with larger nodes indicating more frequent occurrences (Waltman et al. 2010; Perianes-Rodríguez et al. 2016). Links between nodes signify words appearing together, and distinct colors represent topic groups, aiding in understanding the thematic relationships.

Screening involved titles and a subset of abstracts (< 20%), retaining ~10% for deeper analysis. Other documents had other contributions. Newspapers contributed to the socio-political context whereas statistical-agency data provided robust and visual evidence. The availability was higher for service stations than for some other domains.

4.2.2 | Patents

Patent analysis mirrored the scientific literature workflow. They illuminated existing and emerging technologies, organizations' research and development (R&D) intentions, and technology-oriented perspectives. The identified documents included advances toward vehicle energy independence (e.g., algorithms/devices for terminal efficiency/location; on-board energy generation), as well as facilities for drones/airborne vehicles. For more details about patents and number of related theme documents per country, category, applicant and year, see Appendix I.

4.2.3 | Interviews (Delphi)

Interviews largely confirmed document-derived trends: 16% of total trends were unique to interviews; 22% overlapped. While experts often expanded on identified trends, contributing valuable contextual insights, they were instrumental in providing 29 visions for the future. These comprehensive visions played a direct role in constructing prospective scenarios in subsequent steps.

Constraints were predominantly interview-unique (87%), underscoring their role in capturing conditional factors (often absent in documents) that influence the pace of change. The four most-cited trends were: electricity (17), electric vehicles (17), government interventions (16), and hydrogen (12). Table 2 shows the most addressed topics during interviews.

4.3 | Data Synthesis and Interpretation

To organize disparate data types, we used a "system variables × conditions of the future" matrix (see Methods section). The values were 1 (strong/direct), 0.5 (moderate/indirect), 0 (no significant impact). Then, the totals were color-coded (> 10 [yellow], > 20 [orange], > 30 [red]).

The primary objective of this step was to establish correlations, providing a coherent synthesis of information by identifying similarities and cause-and-effect phenomena within the dataset. This structured approach enhances the overall understanding of the interplay between various elements, paving the way for meaningful interpretations and insights. Below, Table 3 exemplifies the QFD matrix type developed for the study.

4.4 | Scenario Crafting and Storytelling

Upon comprehending the intricacies of the system, identifying key variables, and assessing trends and constraints (conditions of the future), the subsequent step involved delineating the parameters for the scenarios. It's considerable that the process of interpolating and structuring this data inherently provided researchers with a nuanced understanding, potentially leading to the conceptualization of diverse future scenarios even before formal scenario construction.

Table 4 presents an illustrative example of a random configuration, and it's noteworthy that the matrix encompasses a total of 120 potential configurations (excluding additional lines). This methodical approach ensured an exhaustive exploration of diverse scenarios, contributing to a rich tapestry of conceivable future states.

Below, example of GMA (Ritchey 2011) randomizing scenario parameters.

```
['according to the percentage',
 'teenager', 'hydrogen', 'stand alone',
 'electric', 'underground',
 'touch screen', 'highway']
['according to time', 'adult',
 'induction', 'gratuity/data',
 'electric', 'parking', 'manual',
 'highway']
['according to the percentage',
 'seniors', 'induction',
 'generate own energy', 'flex',
 'top buildings', 'voice command',
 'rural']
['according to the percentage',
 'employee', 'wind',
```

TABLE 2 | The most addressed topics during interviews.

Trend	Citations	Constraint	Citations	Vision of future	Citations
Electricity	17	Battery	11	Charging station home	10
Electric vehicles	17	Recharge duration	9	Attractiveness	10
Political intervention	16	Energy price	8	Commercial charging	6
Hydrogen	12	Winter period	7	User participant	5

TABLE 3 | System variables × conditions of the future matrix.

		Variable	Fuel	Refueling time	Guiding user	Milestone	Energy storage	...	Total
Condit. factor	Cl.	Behavior							
Cashless society	S/Ec.	1	0	0	0.5	0	0	...	11
ZEV matriculation	S/Ec.	1	1	1	1	0	1	...	20
Recharging point in cities	Env.	1	1	1	1	1	1	...	30
Stand-alone service stations	Env.	1	0	0.5	1	1	0	...	32
Aging population	S.	1	0	1	1	1	0	...	32
Solar energy	T.	1	1	1	0.5	0	1	...	15
Digital twins	T.	1	0	0	0	0	0	...	10
...	...	...	...	...	...	...	...	...	...
Total			43	30.5	14.5	24.5	20.5	...	...

Note: Condit. = Conditioning; Cl. = Classification; S/Ec. = Socio-economic; Env. = Environmental; S. = Societal; T. = Technological; ZEV = zero-emission vehicle.

TABLE 4 | Example of random combinations.

Activity/Need	Stakeholder/user	Energy	Vehicle	Location	Technology/interface
Refuel completely	Young adult	Hydroelectricity	Electric	Urban	Voice command
According to time	Seniors	Hydrogen	Flying	Countryside	Virtual reality
According to %	Adult	Electricity induction	Light-duty	Roads/highways	AI
Maintenance	Family	Wind source	Heavy-duty		Internet of things
Information	Employee	Solar source	Autonomous		Cellphone
Milestone	Minor age	Nuclear	Shared		Manual

```
  'generate own energy', 'autonomous',
  'work place', 'manual', 'rural']
 ['refuel completely', 'young adult',
  'hydrogen', 'stand alone', 'shared',
  'top buildings', 'decentralized',
  'urban']
 ['according to the percentage', 'seniors',
  'solar', 'profit/vol', 'shared',
  'work place', 'decentralized', 'urban']
```

For the six parameters we defined above, we assigned values based on the research. In the random combination that GMA produces for one iteration as shown in Table 4, we have the following scenario: a young adult who is the owner of an autonomous car needs maintenance and uses induction in the urban area, using artificial intelligence (AI).

Two examples of storyline scenarios generated by this study are shown below (Scenario I—Figure 3 and Scenario II—Figure 4).

4.4.1 | Scenario I

A young adult wishes to have his autonomous vehicle serviced and updated. He schedules it for the night so that the vehicle can drive itself to an underground space where it can perform these tasks. There, the vehicle will park and connect via wifi to the store. The facility will be able to scan it and make the updates while performing the usual tire inflation and fluid change. In addition, the vehicle will automatically recharge its battery through an induction router located in the parking space. The garage uses electricity provided by the grid. The user can allow services, connect, and track the status of his vehicle through a cell-phone application. Furthermore, minor updates can be made when the vehicle is parked with access to a private wifi network. The vehicle will be ready at a scheduled time and will finally pick up its owner for a new day of work. The vehicle will alert the owner, according to the configuration chosen by him, of any repair needs and for scheduling the next major maintenance.

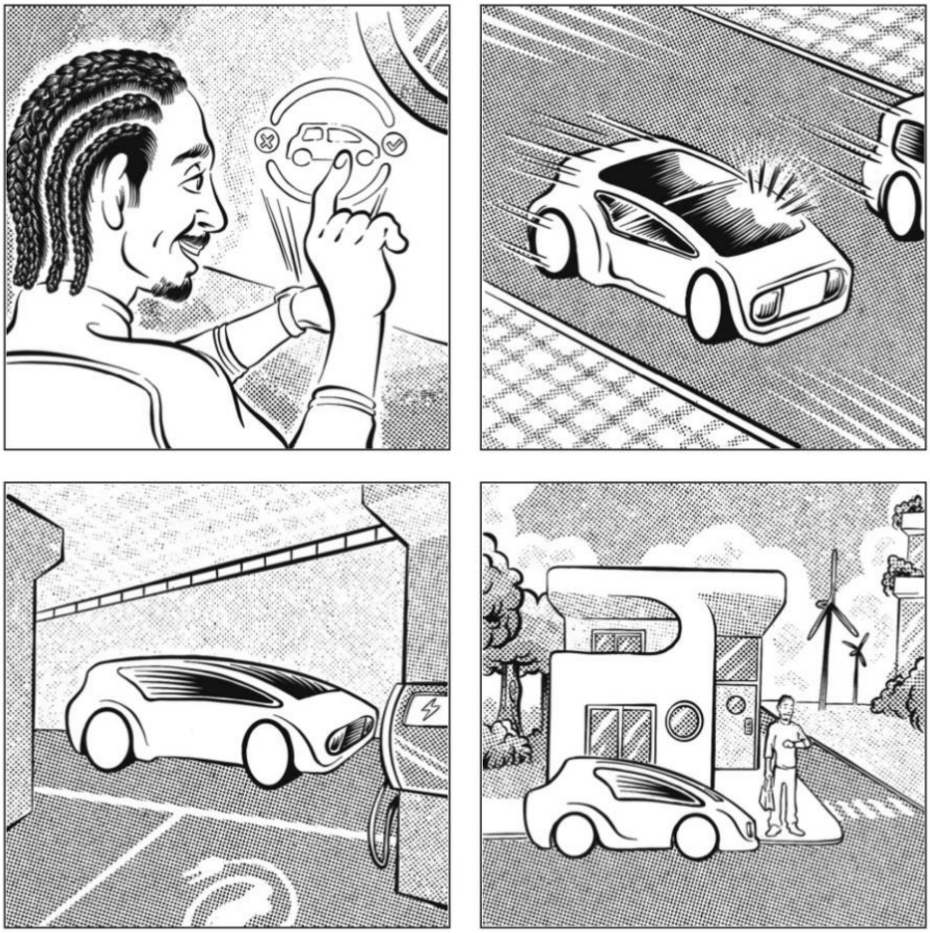

FIGURE 3 | Scenario Illustration I. Illustrator: Flavio Duarte.

4.4.2 | Scenario II

An elderly woman wants to recharge her electric car by 30% on the road during a short trip. The car's navigation system locates the next service station before it reaches its remaining battery capacity of 15%. After locating the station, the woman drives to the location. When she arrives, she parks in the indicated space and starts the pairing between the vehicle and the service station. The woman accepts the pairing through the on-board screen and the station's virtual assistant greets her and starts the service. She makes selections using voice-activated commands. The animated virtual assistant asks her if she will get out of the car and use one of the services offered on the site (catering, accommodation or entertainment). The woman says she will stay in the car. The assistant asks if she wants some type of product (beverages, food, etc.) to be delivered to the spot she occupies (14A). She says no. It asks if she would like to charge by minute, battery-charge percentage or amount of money. She suggests by percentage. It asks how many percent she wants to recharge. She answers 30%. It asks for a few seconds to calculate time and price. It informs her that the service will take 15 min and cost 5 dollars. She accepts and the recharge starts through a robotically coupled cable. The lady puts her streaming service on the onboard screen and continues to watch her series from where she left off. After the estimated time, the assistant interrupts saying that the objective was accomplished and that she can see the receipt on the store's app or through the app of the registered credit card. It asks if the woman wants something else. She answers no. Then the guide ends the service and thanks her, releasing the car and ending the pairing. This roadside station generates its own energy through solar panels and wind towers.

4.5 | Scenarios Validation

To ensure differentiation and coverage of uncertainty across contexts (Wilson 1998; van der Heijden 2011), we selected 12 scenarios grouped into urban center, highway, and rural/outskirt contexts. We first positioned scenarios on an uncertainty (1–5) × disruption (1–5) matrix (Figure 5). We then conducted an expert appraisal of plausibility using within-group 3/2/1 voting (Table 5) and assessed temporal horizon by identifying the shortest- and longest-horizon scenarios per group (Table 6). Finally, experts confirmed internal consistency ("makes sense/does not make sense") for all scenarios.

In the urban set, Scenario H received the highest plausibility score, while Scenario I was consistently assessed as the most distant in time.

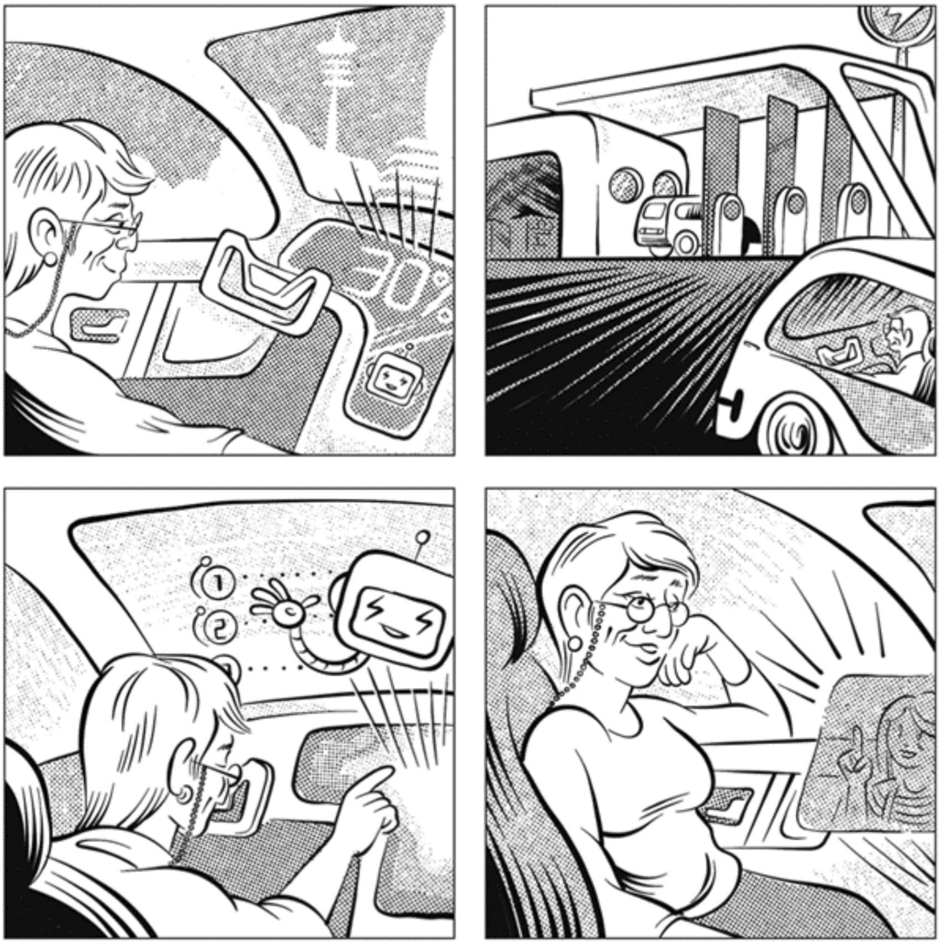

FIGURE 4 | Scenario Illustration II. Illustrator: Flavio Duarte.

Although it is assumed that all 12 selected scenarios represent different uncertainties, it was confirmed that in each group, there are at least 2 scenarios with 3 major uncertainties. Scenarios J, K, and L are not only rural and/or outskirt scenarios. They were chosen for the rural group precisely to stimulate discussion about their suitability and possible new scenarios and insights. The validation process continued with the participation of experts and stakeholders (as described in the Methodology section) (Berkhout et al. 2002). The participants voted on plausibility (Wilson 1998; van der Heijden 2011) in each group by assigning the scores 3, 2, and 1 to the most plausible scenarios (with 3 being the most plausible in the group). Table 5 below shows the degree of plausibility of the scenarios presented according to the respondents.

We leveraged the insights gathered from our engagement with various experts to delve into an additional analysis: identifying the scenarios they perceive as having the longest or shortest time horizon. The respective weightings for these considerations are presented in Table 6 below.

From this two-dimensional analysis, we created a plausibility versus time matrix for the scenarios presented (Figure 6).

Finally, they (experts) validated whether the scenarios presented were consistent and made sense, in a "yes" or "no" evaluation, for a revalidation of the consistency criterion. For them, all the scenarios are understandable, and the combination of logic in each scenario ensures that there is no built-in internal contradiction.

5 | Discussion

5.1 | Implications for Mobility-Transition Research

We treat the scenario as an analytical device to surface mechanisms of incumbent adaptation under deep uncertainty, rather than as a forecast or a firm-specific business plan.

Most electrification futures work treats charging infrastructure as an aggregate outcome of policy and adoption trajectories (LaMonaca and Ryan 2022). Our scenario *ensemble* surfaces how an incumbent, place-based infrastructure (the forecourt network) can actively shape transition dynamics through site conversion, service redesign, and coordination with grid and retail ecosystems. This actor-centered view complements research on charging-market roles and governance by specifying what adaptation looks like at the service-system level and why pathways diverge by location and trip purpose (urban dwell/space constraints; highway throughput and amenity bundling;

rural resilience and prosumer participation). This shifts the unit of analysis in mobility-transition debates from vehicles/policy alone to the reconfiguration of incumbent service infrastructures that mediate everyday mobility.

A second contribution is to show that the transition is unlikely to be uniform: the same electrification pressure yields distinct pathway archetypes (destination hubs, distributed stands/micro-charging, and prosumer-oriented energy nodes), implying that "one-size" infrastructure policy or firm strategy will misspecify required capabilities and investment sequencing. This also responds to critiques that mobility futures can become constrained by incumbent imaginaries by explicitly widening the set of plausible service configurations beyond straightforward "station-to-charger" substitution (Hawxwell et al. 2024).

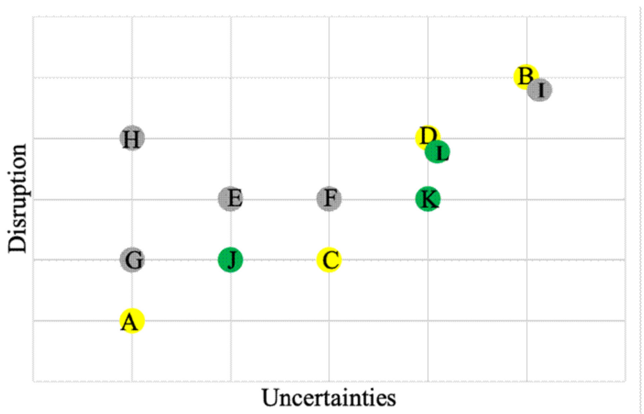

FIGURE 5 | Scenario matrix: Disruption versus uncertainties. *Note:* Green = Rural and/or outskirt zones; Yellow = highways; Gray = urban centers. A = Major center—elderly woman stops to recharge during her trip at a center that offers many services, accommodations and entertainment. B = Smart highway—recharging is done by induction on a lane reserved for recharging. C = Stand stations—family stop in a stand for supercharging and tire inflation, distributed on the highway. D = Vehicle auto-recharging—the vehicle partially recharges itself while driving. E = Station building—user recharges his flying electric vehicle at the top of the buildings. F = Underground station—autonomous vehicles are maintained and recharged by induction in an underground station G = Parking station—co-sharing vehicles recharge at their assigned bay, parking center. H = Commercial-centers stations—users go shopping at the mall and the recharge of their vehicle is related to the time and money spent inside. I = Smart city—decentralized charging model at intersections, traffic lights, and mandatory stops, with public-private partnerships. J = Energy Generator Station—Station offers a mix of energy and produces part of its own energy. K = User generates/provides energy—user becomes an active participant in the network and partially fills the role of the service station in its surroundings. L = Battery station—senior with removable battery, inserts the almost empty battery on the station and takes a charged one.

Prior work on electrification futures and charging infrastructure (see Section 2) has largely emphasized macro adoption pathways, network rollout, and policy/market coordination, often treating refueling sites as locations within a system rather than as incumbent service infrastructures that must reconfigure their value proposition (e.g., LaMonaca and Ryan 2022; Sun et al. 2024; Arup 2024). Complementing this, travel-behavior evidence suggests that charging/refueling choices are strongly context- and user-dependent, which implies heterogeneous requirements for public hubs and intermediary services (Dorsey et al. 2022). Our findings extend this received view by showing that the forecourt network's future is not well captured by a single "conversion to charging" narrative: instead, the transition produces place-based pathway archetypes (urban, highway, rural/outskirt) with distinct capability bundles and investment sequencing needs. This reframes the academic question from whether stations convert to how incumbent service infrastructures recombine services, coordination roles, and operational capabilities under prolonged multi-infrastructure coexistence.

Scenario H—viewed as the most plausible and immediate for urban centers—involves users distributing recharging across commercial centers. At the other end of the spectrum, Scenario I—smart cities with integrated charging at road intersections—is considered the furthest in time. For roads, large charging stations offering diverse services and green energy sources are seen as the most imminent, whereas intelligent road concepts are more distant. In rural and outskirt areas, the most plausible and immediate scenario features users actively participating in electricity production, simultaneously acting as energy suppliers and gas stations; experts noted that this scenario, initially short term, may extend into the long term, underscoring the difficulty of validating more distant futures.

While there is some consensus regarding urban-center scenarios, views diverge more for roads, suburbs, and rural areas. The advanced, widely shared discourse on the future of cities may help explain the urban consensus; in contrast, discussions for other zones remain incipient, and prior exposure to more familiar solutions may inhibit acceptance of more radical innovations. It is also possible that the selected scenarios for roads and rural/outskirt areas were not ideal representatives; however, alternative options did not emerge during expert discussions. This indicates the need to identify combinations not yet considered.

In the medium term, spaces are expected to be transformed into parking areas for recharging, including entertainment

TABLE 5 | Sum of plausibility scores for scenarios.

Group	Urban center scenarios					Highway scenarios				Rural/outskirt zone scenarios		
Scenario	E	F	G	H	I	A	B	C	D	J	K	L
Sum of scores	6	10	14	21	3	20	12	12	10	19	20	15

TABLE 6 | Sum of votes scenarios long and short-term.

Group	Urban center scenarios					Highway scenarios				Rural/ outskirt zone scenarios		
Scenario	E	F	G	H	I	A	B	C	D	J	K	L
Long term	0	0	0	0	9	0	7	0	2	4	2	3
Short term	0	0	1	8	0	6	0	3	0	1	5	2

Note: Green = Rural and/or outskirt zones; Yellow = highways; Gray = urban centers.
A = Major center—elderly woman stops to recharge during her trip at a center that offers many services, accommodations and entertainment.
B = Smart highway—recharging is done by induction on a lane reserved for recharging.
C = Stand stations—family stop in a stand for supercharging and tire inflation, distributed on the highway.
D = Vehicle auto-recharging—the vehicle partially recharges itself while driving.
E = Station building—user recharges his flying electric vehicle at the top of the buildings.
F = Underground station—autonomous vehicle is maintained and recharged by induction in an underground station.
G = Parking station—co-sharing vehicles recharge at their milestone, parking center.
H = Commercial centers stations—user goes shopping at the mall and the recharge of his vehicle is related to the time and money spent inside.
I = Smart city—decentralized charging model at intersections, traffic lights, and mandatory stops, with public-private partnerships.
J = Energy generator station—station offers a mix of energies and produces part of its own energy.
K = User generates/provides energy—user becomes an active participant in the network and partially fills the role of the service station in its surroundings.
L = Battery station—senior with removable battery, inserts the almost empty battery on the station and takes a charged one.

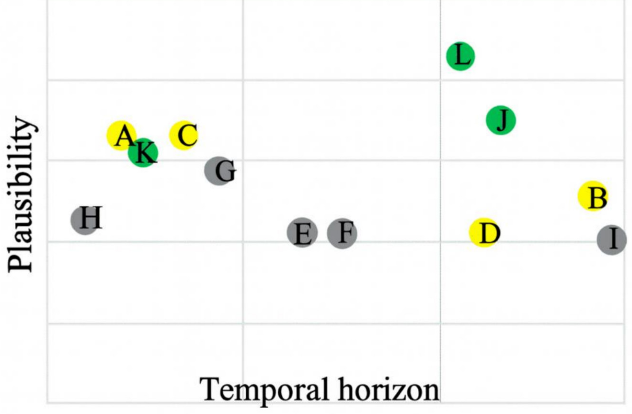

FIGURE 6 | Scenario matrix: plausibility versus temporal horizon.

and catering services. Among highway scenarios, one included conversion into large recharging centers with varied services (e.g., stores and entertainment for children). In addition to such centers, modular automated stations (potentially mobile) appear promising for various regions. More disruptive possibilities include intelligent roads and dedicated recharging sections via induction charging, which are already prototyped in several countries. There is also the possibility of vehicles generating part of their own energy; patents and corporate documents point to efforts toward partial energy independence, suggesting a future where users become less dependent on charging stations.

These energy-generation and storage shifts require physical space, a particular challenge in urban centers. The energy transition pressures turnover time at recharging stations and elevates the value of underground areas and parking structures. In the short term, scenarios in which service stations are unnecessary due to frequent, short-duration recharging (e.g., at supermarkets, shopping centers, and workplaces) already exist. Some disruptive scenarios also consider flying cars and vertical-space utilization for service stations (supported, among other sources, by building-integrated systems for drones). Building rooftops are likely to gain value and open opportunities for innovation. A more distant scenario envisions smart cities with microrecharging at multiple points (e.g., establishments, traffic lights, and street segments), with or without a common backup system.

The scenarios provide design guidance for transition periods in which multiple products and energy sources overlap. Interfaces should be simplified, and users should be guided in ways that mask backend complexity. Scenarios also point to varied energy choices and even user participation in the network. Products should enable multiple technologies, leverage data sharing, and integrate across emerging systems.

Consolidating ecoresponsible consumption patterns and periodic urban exodus indicate that investment only in buildings and education will be insufficient; infrastructure investment remains necessary, especially in hard-to-access locations. Given the chosen system, future research could focus on road and rural scenarios. Urban centers face limited space for diverse energy production, infrastructure, and longer charging times—constraints less severe in rural and road contexts, which may therefore be suitable for disruptive pilots and more distant scenarios.

Experts highlighted electricity as a robust trend (especially salient in Quebec), which produces a third of Canada's electricity through hydroelectric resources. Electric vehicles are widely perceived as the future of transportation despite extant challenges. Government interventions were underscored as socioeconomic trends, including regulatory measures, economic incentives, and ecosystem investments (e.g., bans on gasoline vehicle sales and carbon taxes). Hydrogen was recognized as an important trend, potentially leveraging existing fossil-fuel infrastructure and substituting for electricity when necessary.

In this research context, scenarios with fewer uncertainties tend to be perceived as more likely, whereas the most disruptive scenarios appear as potential threats to the current system. Scenarios with lower uncertainty yet higher disruptive potential warrant increased attention. Table 7 summarizes the set of clues revealed by this study, linking the scenarios, the challenges and risks for gas stations addressed here, the opportunities for them, and the possible innovation needs.

The 12 scenarios outline a spectrum of strategic options that differ in capital intensity, operational complexity, and capability requirements. Scenario A (major highway center) concentrates

TABLE 7 | Scenario implications (summary by scenario A-L).

Scenario	Challenges/risks for gas stations	Opportunities for gas stations	Possible innovation needs
A – Major center (highway mega-center with services, accommodations, entertainment)	High CAPEX and long build times; matching long charging dwell with throughput; coordinating multi-service operations	New revenue streams (retail, food, entertainment); destination positioning; use of green energy	Site master-planning; queue/time management; service orchestration platforms; energy mix integration
B – Smart highway (induction-charging lane)	Technology maturity and regulation; very high infrastructure costs; integration with road authorities	Differentiated highway offering; partnerships on charging-as-a-service	Induction hardware integration; billing/pairing systems; safety and maintenance procedures
C – Stand stations (distributed supercharging + tire inflation on highways)	Network deployment/ maintenance; ensuring utilization; pricing consistency	Wide coverage brand; quick-stop specialty; modular rollout	Modular, possibly mobile station design; rapid setup kits; remote monitoring/ops
D – Vehicle auto-recharging (vehicle generates part of its own energy)	Reduced dependence on stations; uncertain technology timeline	Complementary services (maintenance, upgrades, amenities); backup/peak charging	Integration with self-generating vehicles; diagnostics & update bays; flexible energy offerings
E – Station building (rooftop/flying-vehicle recharge)	Urban space/safety constraints; vertical access logistics	Monetize vertical/rooftop assets; premium urban services	Vertical/rooftop infrastructure; safe docking/ charging interfaces; permitting playbooks
F – Underground station (autonomous vehicle maintained & recharged by induction)	Safety, ventilation, and robotics reliability; connectivity underground	High-throughput, unattended operations; overnight maintenance revenue	Robotic coupling; induction pads; autonomous check-in/pairing; workflow automation
G – Parking station (co-sharing vehicles recharge at parking centers)	Coordinating fleets and bays; variable dwell times; grid load	Fleet contracts; steady utilization; data-driven operations	Bay scheduling; fleet integrations (APIs); smart load management
H – Commercial centers stations (mall/ shop charging linked to time/money spent)	Dependence on retail footfall; peak-time congestion	Retail partnerships; cross-promotions; loyalty programs	Time/Spend-linked billing; navigation & guidance; customer experience tooling
I – Smart city (decentralized micro-charges at intersections/traffic lights/stops)	Urban integration complexity; many small assets to manage	Ubiquitous brand presence; city partnerships; frequent micro-transactions	Distributed asset management; micro-billing; resilient grid interfaces

(Continues)

TABLE 7 | (Continued)

Scenario	Challenges/risks for gas stations	Opportunities for gas stations	Possible innovation needs
J – Energy generator station (mix of energies; produces part of its own energy)	Siting/storage; balancing generation with demand	Lower energy costs; grid services revenue; resilience	On-site generation + storage; energy management systems; safety & compliance
K – User generates/provides energy (prosumer participation)	Regulatory/grid complexity; variable quality/supply	Buy–sell marketplace; community programs; brand trust	Prosumer platforms; bidirectional energy flows; verification & settlement
L – Battery station (removable battery swap, esp. larger vehicles)	Safety/practicality for users; space/weight handling	Ultra-fast "refuel" experience; heavy-duty segment capture	Swap robotics; standardized cassettes; inventory/charging logistics

risk in high CAPEX and multi-service coordination, yet offers diversified, multi-service revenues. It therefore depends on rigorous master planning and service-orchestration competence. Scenario B (smart highway induction lane) hinges on regulatory and technical feasibility and would require differentiated partnerships; implementation capability centers on induction integration, reliable billing/pairing, and codified safety procedures. As for scenario C (distributed "stand" stations), the attention shifts to network utilization and consistent quick stop positioning, supported by modular or mobile designs and robust remote operations.

Then, scenario D (vehicle auto-recharging) implies declining dependence on stations, reframing the station's role toward complementary services. The diagnostic and update capacity and flexible energy offerings become salient. Scenario E (rooftop/flying-vehicle recharge) introduces urban space and safety constraints while enabling premium services. Vertical access and safe docking are core needs not very much aborded by society. Scenario F (underground automated station) emphasizes safety, ventilation, and robotics reliability for unattended, overnight operations, with requirements in robotic coupling and induction pads.

Scenario G (parking-center recharge) focuses on fleet/bay coordination to sustain utilization, necessitating scheduling systems, fleet Application Programming Interface (APIs), and load management. Scenario H (commercial-center charging) is sensitive to footfall and peak congestion but benefits from retail partnerships and loyalty programs. Here, time- or spend-linked billing and guidance are central. About scenario I (smart-city micro-charges), it requires deep urban integration and distributed asset management, supported by micro-billing.

Scenario J (energy-generator station) reframes the site as a producer, raising sitting and storage issues but creating energy-cost and grid-service opportunities. Once more, on-site generation, storage, and energy management systems are pivotal. Scenario K (prosumer participation) introduces regulatory and quality variability, oriented to marketplace and community programs with bidirectional flows and settlement. Finally, scenario L (battery-swap station) addresses ultra-fast "refuel" for heavy-duty use but carries safety and space-handling demands, relying on swap robotics, standards, and inventory logistics. Collectively, these scenarios suggest differentiated capability pathways and staged investment logics aligned to context and risk. They not only support corporate preparation but also suggest that, at the governmental level, concentrating investments on incremental advances may be inadequate as it is today. The risk of missing disruptive leaps implies that substantial investments could be lost if rapid adaptation is required.

In conclusion, we demonstrate three transition pathway archetypes and what they imply:

> Archetype 1. Highway destination hubs: high CAPEX, orchestration, on-site energy management.
>
> Archetype 2. Urban distributed charging/parking-fleet centers: scheduling, load mgmt, platform integration.

Archetype 3. Rural/outskirt prosumer nodes: bidirectional energy, verification/settlement, resilience logic.

5.1.1 | Barriers and Feasibility Assessment

We treat feasibility constraints as *implementation frictions* (not scenario "truth"), to clarify what must be resolved for each pathway to be viable.

Several pathways depend on permitting, zoning, and utility interconnection procedures that can be slow and fragmented for high-power charging projects, especially when multiple agencies are involved (municipality, road authority, fire/safety, and distribution utility). These issues are most pronounced for scenarios requiring right-of-way occupation or distributed curb/intersection assets (Scenario I), and for scenarios that introduce new infrastructure categories (induction lanes, Scenario B) where standards and liability regimes may be underdeveloped. Interconnection/energization timelines are repeatedly documented as a bottleneck for public fast charging deployment and can materially affect station economics (Anand et al. 2025).

High-power hubs (Scenario A) and fleet/parking formats (Scenario G) are constrained by local grid capacity, transformer upgrades, and operational load management (peak coincidence). Distributed formats (Scenario I) increase system complexity by multiplying assets requiring monitoring, cybersecurity, and maintenance logistics. Scenarios involving on-site generation/storage (Scenario J) and bidirectional/prosumer participation (Scenario K) further require robust metering, controls, power-quality management, and (in many jurisdictions) revised interconnection rules to enable safe two-way flows (Dimatulac et al. 2025).

User acceptance hinges on perceived convenience, waiting time, safety, accessibility, and trust in billing/availability. These issues become salient for decentralized public charging (Scenario I) and for automated/novel service systems (Scenario F, Scenario L). Equity is also central. Dense urban contexts and households without home charging increase reliance on public infrastructure, which makes the reliability and accessibility of public charging a socio-political constraint rather than a purely technical one (Lee et al. 2024; Yu et al. 2025).

While full techno-economic modeling is beyond this paper's scope (and proposed as future work), the scenarios can be economically differentiated using three robust drivers: CAPEX intensity, utilization sensitivity, and electricity tariff/interconnection exposure. High-CAPEX hubs (Scenario A) require consistently high utilization and diversified on-site revenues (retail/food/services) to mitigate payback risk; they are also exposed to grid upgrade costs and demand charges where applicable. Distributed "stand" concepts (Scenario C) reduce site CAPEX per node but become sensitive to network utilization and operations costs. Retail-linked dwell-time scenarios (Scenario H) benefit from cross-subsidy/logistics partnerships but are sensitive to peak congestion and site access. Tariff structures (especially demand charges) are widely noted as a major cost component for fast charging and can distort viability when utilization is low or peaky, making smart load management and pricing essential (McFarlane et al. 2019; Bhardwaj 2024).

For generation/storage (Scenario J) and prosumer participation (Scenario K), the economic case depends on the value of avoided energy costs, grid services, and settlement arrangements. Therefore, it is tightly coupled to regulation and market design rather than technology alone.

5.2 | Implications for Scenario Planning and Design Research

Several authors highlight the inherent difficulty linked to the human ability to project oneself into the distant future and even to articulate current needs (Barczak et al. 2009; Ulwick 2013; Engeler 2017). Other authors argue that the key to foresight lies in understanding the root of current needs and extending them into a future context, asserting that "primary" needs will not change over time (e.g., moving around, communicating, and resting) (Brangier et al. 2019).

We sought to work from a complementary perspective, using the rational tools of multiple disciplines and combining them with creative methods. In addition, we involved stakeholders, in line with the design literature and at the same time with a social constructivist perspective. We believe that the foresight exercise is both "a social construction and a social construction mechanism," as Fuller and Loogma (2009) put it.

Scenario validation was distributed across scenario development, stakeholder and expert evaluation (Berkhout et al. 2002; Kahn 2012), and integration into NPD (Saritas 2024), drawing on Wilson (1998) and van der Heijden (2011). This distributed validation (spanning creation, evaluation, and utilization) supports the FE stages in development (Simms et al. 2021). Following the consistency criterion (Wilson 1998; van der Heijden 2011), scenarios are grounded in reliable sources and cross-analysis to build coherent logics. Differentiation is addressed by selecting distinct scenarios among clusters. Plausibility is examined with experts and stakeholders through a plausibility-versus-time matrix. At least two scenarios reflect uncertainties (van der Heijden 2011), as analyzed and displayed in matrices. Finally, relevance and novelty (Wilson 1998; van der Heijden 2011) are considered through their usefulness. Here, they fit PPM and TRM, as they have the potential to challenge conventions and catalyze disruptive innovation.

At the macro level, goals such as refueling/recharging and payment were deemed less volatile, informing NPD strategies. System understanding and variable identification can also be achieved through questionnaires, interviews, literature analysis, focus groups, abstraction–decomposition hierarchy, requirement analysis, and the KJ method (Rosson and Carroll 2007; Annett 2003; Phipps et al. 2011; Kawulich 2005; Ciesielska et al. 2018). Retrospective newspaper research is time-consuming but provides socio-political signals. Thus, statistical data offered robust, government-supported data. The interview analysis process was also time-intensive (transcription and coding). Experts uniquely identified 87% of constraints, providing insight into conditional factors that influence the pace of change and are often absent from documents. They also contributed 29 visions for the future. So, their contribution proved to be essential.

Scenarios are communicative and can facilitate tools that materialize prospective technological, market, and societal information. They can be structured and debated via matrices (Cheng 2002; Rhydderch 2017), trial sessions (Kahn 2012), and trajectory construction (Ratcliffe 2006). We only presented part of the possibilities. They are also consistent with other FE strategies (Oliveira and Rozenfeld 2010; de Alcantara and Martens 2019). The scenario building helped here to identify and understand trends and constraints. It could enable more informed decisions, alignment with key system variables and goals, and prioritization of product-development options (Dell'Era et al. 2018). This supports a more comprehensive FFE aligned with fundamental factors.

We propose that scenarios should be evaluated by degree of uncertainty and impact on the system, and by strategic fit with the company's position. They may be:

- Classified and evaluated with scorecards reflecting portfolio-deployment criteria.
- Analyzed along axes such as market attractiveness, financial reward, technical feasibility, and risk
- Used in matrices to inspire discussion, compare business strategies, assess product alignment, and generate product ideas and requirements.
- Integrated into portfolio management through various methods. We
- Applied by service stations to acquire and develop capabilities (e.g., roadmaps) and expand the scope of operation.

6 | Conclusion

This study proposed and applied a structured approach to generate far-future prospective scenarios of use for gas stations amid transport electrification. Grounded in Design Research Methodology, the process integrated (1) field observation and HTA to define system variables; (2) multi-source environmental scanning (patents, literature, policy, and media) and interviews with experts to elicit future conditions; (3) a QFD-inspired impact matrix to synthesize relationships; (4) GMA with ideation to craft scenario logics and narratives; and (5) stakeholder/expert validation against established criteria (consistency, differentiation, plausibility, relevance, and novelty). Together, these steps produced a coherent, replicable pipeline for imagining heterogeneous futures while maintaining traceability from evidence to scenario design.

Empirically, the scenario ensemble recenters the underexplored "gas station" actor and surfaces differentiated pathways across urban, highway, and rural/outskirt contexts. Experts judged "commercial-center charging" as the most immediate in urban areas, whereas "smart-city micro-charging" sits furthest on the time horizon. On highways, large multi-service charging hubs appear near-term, with induction-enabled roads more distant. In rural/outskirt contexts, prosumer energy participation emerges as both plausible and potentially enduring, highlighting how user-provided energy can complement traditional station roles. These findings underscore that transition trajectories will be uneven across geographies and formats, and that portfolio choices should be staged to context, risk, and capability requirements.

Methodologically, the work contributes to a practical, scenario-driven linkage between front-end innovation activities and strategic management tools. The variables versus conditions matrix clarifies where future signals most disturb current functions and experience elements, while the plausibility versus time mapping supports prioritization for near-, mid-, and long-term exploration. The distributed validation approach (spanning creation, expert appraisal, and intended use) helps guard against internally inconsistent or redundant futures and provides actionable inputs for TRM and PPM.

Theoretically, the study contributes to scenario-planning scholarship by making the scenario-construction logic more traceable and design-operationally usable: it explicitly links task/service functions to external uncertainties, combining structured synthesis (e.g., cross-impact/matrix reasoning) with scenario logics and explicit evaluation criteria. This responds to recurring calls for clearer definitions, integration of methods, and evaluative rigor in scenario work (Chermack 2005; Amer et al. 2013; Hussain et al. 2017; Spaniol and Rowland 2019; van der Heijden 2011). In addition, by treating the forecourt network as an incumbent service infrastructure and not merely an infrastructure "site," the study complements macro electrification futures and shows why transition pathways and capability needs diverge by geography and trip purpose (LaMonaca and Ryan 2022; Dorsey et al. 2022).

Practically, the scenarios delineate the distinct capability of roadmaps. High-CAPEX highway "destination hubs" require master-planning, service orchestration, and on-site energy management. The distributed "stand stations" favor modular deployment and remote operations. The urban "parking/fleet centers" call for bay scheduling, API-based fleet integrations, and smart load management. Thus, those prosumer-rich settings demand bidirectional energy, verification, and settlement platforms. For policymakers, the coexistence of liquid-fuel and electric infrastructures over many years implies that gas-station owners should not be sidelined: targeted incentives, permitting playbooks, and public-private coordination can mitigate transition risks and leverage existing forecourt assets to accelerate sustainable mobility.

We acknowledge the limitations. First, the empirical application centers on Canada (with emphasis on Quebec) may limit direct transferability to regions with different energy mixes, urban forms, and regulatory regimes. Second, while expert panels were diverse, the number of interviewees was small, and scenario selection inevitably reflects bounded sets of combinations. Alternative, equally plausible configurations may exist. Third, signals and relationships were time-bounded to collected sources. As conditions evolve, matrix weights and plausibility appraisals may shift. Finally, scenario narratives privilege qualitative logics; complementary quantitative modeling (e.g., demand, dwell time, and grid impacts) was beyond scope.

Future work could: (a) replicate and contrast the approach across jurisdictions with distinct policy and grid contexts; (b) integrate techno-economic and spatial models to test business-model viability (throughput, energy costs, grid constraints) under selected scenarios; (c) run longitudinal Delphi rounds to track shifting plausibility and time horizons; (d) examine user equity and access, especially for drivers without home charging; and (e) operationalize scenario outputs into rolling PPM and TRM to inform staged investments and partnership strategies. Also, periodic re-evaluation, triggered by new signals or predefined intervals, should be institutionalized to keep scenarios decision-relevant as the transition evolves.

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Conflicts of Interest

The authors declare no conflicts of interest.

Endnotes

[1] E.g., Shell plc. (2024, March). *Energy transition strategy 2024*. Shell. Available: https://www.shell.com/sustainability/climate/shell-energy-transition-strategy.html.

[2] Shell, 2024: Shell Annual Report and Accounts and Form 20-F 2024.

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Appendix I

TABLE A1 | Number of patents per country or group.

Country/Region	No. of documents
China	768,971
U.S.A.	434,309
Japan	366,788
P.C.T. (International)	185,551
European P.O.	181,933
Republic of Korea	155,644
U.K.	103,009
Germany	100,840
Canada	48,163

Note: No. = Number.
U.S.A. = United States of America;
P.C.T. = Patent Cooperation Treaty;
P.O. = Patent office;
U.K. = United Kingdom.

TABLE A2 | Number of patents per applicant.

Applicant	No. of documents
Hyundai Motor Co.	49,779
Honda Motor Co. Ltd.	47,590
Toyota Motor Co.	47,097
Denso Co.	31,488
Ford Global Tech. LLC	26,087
Nissan Motor Co. Ltd.	24,614

Applicant	No. of documents
Toyota Jidosha Kabushiki Kaisha	24,058
Kia Motors Co.	21,171
Robert Bosch GmbH	20,944

Note: No. = Number.

TABLE A3 | Number of patents per International Patent Classification (IPC).

IPC code	No. of documents
B60R	314,803
B62D	205,896
G08G	130,023
B60L	126,001
B60W	121,510
B60T	92,171
F16H	88,613
B60N	84,751
B60J	75,692

Note: No. = Number.
B60R = Vehicles, vehicle fittings, or vehicle parts, not otherwise provided for;
B62D = Motor vehicles; trailers;
G08G = Traffic control systems for road vehicles;
B60L = Electric propulsion of vehicles; supplying electric power for vehicles; magnetic suspension/levitation;
B60W = Conjoint control of vehicle sub-units; hybrid drive control;
B60T = Vehicle brake control systems or parts thereof;
F16H = Gearing;
B60N = Vehicle passenger accommodation or interior fittings; seats;
B60J = Windows, windscreens, non-fixed roofs, doors; operating or locking devices therefor.

TABLE A4 | Number of patents per year (2013–2021).

Year	No. of documents
2013	67,282
2014	79,016
2015	92,717
2016	99,617
2017	144,771
2018	190,890
2019	215,265
2020	253,305
2021	209,190

Note: No. = Number.