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Roadblocks to fuel-cell electric vehicle diffusion: Evidence from Germany, Japan and California

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ABSTRACT

Fuel cell electric vehicles (FCEV) are diffusing slowly, well below historical expectations and government targets. To elucidate key factors that may explain this sluggish growth, we identify barriers in three influential markets: Germany, Japan and California. Combining data from 59 interviews and secondary documents, we examine each market from four dimensions: (i) vehicle production, (ii) supporting infrastructure, (iii) vehicle demand, and (iv) institutions. Findings reveal a web of systemic and self-reinforcing barriers hampering market formation in all four dimensions. We also find that stakeholders perceive FCEV market barriers in relation to competing technologies; namely battery electric vehicles (BEVs). Faster market growth and lower hurdles for BEVs are thereby raising the relative barriers for FCEVs, further hampering the latter's deployment potential. Findings thus reveal the importance of considering interactions between different technological systems when studying diffusion. They also provide valuable hints for industry and government to confront these systemic barriers.

1. Introduction

The century-long domination of the petroleum-powered internal combustion engine is waning as electric drivetrains encroach increasingly into the road vehicle market. The global stock of electric vehicles reached 11 million in late 2021, growing tenfold in just five years (IEA, 2021a). Multiple forces are propelling this transition. In addition to concerns linked to climate change, air-pollution and dependence on foreign oil imports, electric drivetrains are revolutionising the driving experience through digitalisation, automation and connectivity (Sheller and Urry, 2016, Sperling, 2018). In parallel, numerous countries have announced imminent bans on internal combustion engines (Plötz et al., 2019, Meckling and Nahm, 2019).

Two propulsion technologies are principally driving the electrification of road vehicles: battery electric vehicles (BEVs) that run solely on batteries and electricity, and fuel cell electric vehicles (FCEVs) that run on electricity produced onboard from hydrogen.

Complete electrification of the global vehicle stock will likely require several decades (Bento and Wilson, 2016, Hadjilambrinos, 2021), and both technologies can help accelerate this by co-existing and complementing respective strengths and weaknesses (Ajanovic and Haas, 2019). Yet particularly in the passenger vehicle market, BEVs and FCEVs are often framed as being in competition (Van de Kaa et al., 2017, Knüpfer et al., 2021). Moreover, the former is dominating sales globally. With a mere 43,000 vehicles in circulation in late 2021 (IEA, 2022b), FCEVs are 'trickling' rather than 'flooding' into markets (Pollet et al., 2019). Furthermore, relative to their BEV counterpart, FCEVs have a shorter existence in the marketplace; while Nissan's *Leaf* and Chevrolet's *Volt* were first sold in 2010, Toyota's *Mirai* has only been commercially available since 2015.

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Despite the dominance of BEVs in electric vehicle sales, FCEVs can complement their battery counterpart with numerous advantages (IEA, 2019, Cano et al., 2018). In addition to long driving ranges and rapid refuelling times (Li and Kimura, 2021), FCEVs offer an electric mobility solution for consumers like renters or apartment dwellers unable to install home chargers (Hardman and Tal, 2018). Hydrogen can also decrease exposure to looming and unsolved problems facing the BEV market; namely the recovery and recycling of used batteries (Dawson et al., 2021) and dependence on critical raw materials like cobalt and nickel in battery making (Delloitte, 2020). Not only are reserves of these materials limited, but supply chains are vulnerable to interruptions and cost risks (IEA, 2021b). This is not mention the tremendous socio-ecological impacts caused by extraction and refining (Sovacool et al., 2020). Deploying FCEVs in the passenger market can also generate valuable lessons for other transport applications like heavy-duty, helping to cut the costs of common components like fuel cells through economies of scale (Trencher, 2020). Additionally, hydrogen supply chains for transport can be coupled with other industries like chemicals and steel, thereby spurring their decarbonisation (Li and Kimura, 2021, Chaube et al., 2020).

Recognising such advantages, policymakers, automakers and energy suppliers in numerous regions across Asia, Europe and North America have collaborated over the past two or more decades to accelerate the deployment of FCEVs and refuelling stations while also supporting BEV diffusion. Among these regions, Germany, Japan and California are three strategically important markets. Not only has each built up an extensive refuelling infrastructure, California’s and Japan’s on-road fleet of roughly 10,100 and 6,710 FCEVs respectively (see Table 2) are the highest in the world after Korea (the latter’s fleet reached over 19,600 in late 2021 (IEA, 2022a)). Furthermore, Japan and Germany are home to a globally powerful automotive industry that has actively developed and commercialised fuel-cell technologies (Bento, 2010, Ehret and Dignum, 2012, Trencher and Edianto, 2021, Trencher et al., 2020b).

Yet growth in each these markets is slow and vastly below historical expectations and government targets. Japan, for instance, has reached only 17 % of the goal to achieve 40,000 cumulative FCEV sales by early 2021 at the time of writing. Meanwhile, Germany’s fleet only crossed 1,000 FCEVs in late 2021. This sluggish growth is somewhat paradoxical. Stakeholders in Germany, Japan and California have historically enjoyed considerable funding and policy support (Haslam et al., 2012, Lipman et al., 2013, Budde et al., 2012). Furthermore, over the past two decades, incumbent automakers and fuel suppliers have injected sizable funds in R&D, vehicle development and infrastructure preparation (Bento, 2010).

To elucidate key reasons that may explain the sluggish diffusion of FCEVs in the passenger market, this empirical study identifies and compares the barriers hampering their production and adoption in Germany, Japan and California. We pursue this objective by drawing on a dataset comprised of 59 interviews and diverse documents.

This study advances the literature in three ways. First, we combine mobility literature with theory from socio-technical and technological innovation systems to develop a four-dimensional framework. This allows us to systematically and holistically identify the interconnected and self-reinforcing barriers arising in each dimension while mapping out their negative consequences for market development. Second, we distinguish between the absolute and relative nature of systemic barriers, demonstrating how rapid development of one technological innovation system (that of BEVs) can impose relative barriers on another system (that of FCEVs). Though the core focus of our analysis is on the internal barriers within the FCEV market, our empirical evidence reveals several insights into the influence of external factors, particularly those stemming from other electrification technologies, like BEVs. Third, many studies examining obstacles to FCEV adoption rely on theoretical or predictive assessments (Ajanovic and Haas, 2020, Saritas et al., 2019, Apostolou and Welcher, 2021) or early experiences in immature markets (Hardman et al., 2017). In contrast, our study draws on empirical experiences sourced from semi-structured interviews with experts in government, industry and research institutes in each market we examine.

In the following sections, we introduce the literature underpinning our analytical approach before outlining methods and introducing the FCEV market in Germany, Japan and California. In the findings, we firstly examine and compare the main barriers impeding FCEV diffusion in each market. We then view these systemically, identifying interactions and self-reinforcing relationships. We conclude by summarising key messages and extracting implications for theory and policy.

2. Theoretical perspectives

2.1. Four-dimensional framework and underpinnings in literature

To explain the multiplex dynamics that influence the transition to electric mobility, scholars (Trencher, 2020, Greene et al., 2020, Dua et al., 2021, Dijk et al., 2020) frequently view market creation from four dimensions: (i) vehicle production, (ii) supporting infrastructure, (iii) vehicle demand and (iv) institutions. Each perspective is summarised alongside examples of associated barriers in Table 1. Beyond the mobility domain, this four-pronged view is also discussed in early scholarship on technology and innovation policies (Steinmueller, 2010) as well as on socio-technical transitions. To illustrate the latter, Geels (2004) conceived road transport systems as two interconnected domains of technology production and application in addition to infrastructure and institutions (e.g. regulations and standards). Given this congruence across the mobility and innovation literature, our study too departs from this analytical foundation. Concretely, these four dimensions provide an analytical structure for empirically identifying the barriers hampering the adoption of FCEV passenger vehicles in our three cases.

Table 1
Four dimensions affecting the market creation of electric mobility (FCEVs, BEVs etc.).

Category	Focus	Examples of barriers	Key literature
Vehicle production	Automakers	• Low number of automakers producing vehicles • Low economies of scale in vehicle or component production • High cost of producing vehicles or components • Environmental impacts caused by manufacturing vehicles and components	• Pollet et al. (2019); Bergman (2019); Olabi et al. (2021) • Pollet et al. (2019); Staffell et al. (2019) • Ajanovic and Haas (2020); Cano et al. (2018); Asif and Schmidt (2021) • Sovacool et al. (2020)
Infrastructure	Energy suppliers	• Inadequacy of recharging or refuelling stations to support vehicle diffusion • High construction or operational costs • Low profitability for recharging or refuelling stations	• Leibowicz (2018); McDowall (2016) • Cano et al. (2018) • Ajanovic and Haas (2020)
Demand for vehicles	Vehicle users	• Psychological barriers that impede demand for vehicles (e.g. aversion to high purchase costs or range anxiety) • Low public awareness or acceptance for hydrogen or battery drivetrains • Negative perceptions of environmental benefits from battery or hydrogen production and power for recharging	• Biresselioglu et al. (2018); Cano et al. (2018) • Van de Kaa et al. (2017); Astiaso Garcia (2017); Greene et al. (2020) • Hardman et al. (2017); Berkeley et al. (2017)
Institutions	Governments and rule-making bodies	• Laws or regulations that raise costs or impede investments in market creation • Lack of standards and protocols to minimise uncertainty around dominant technological configurations (e.g. charging or refuelling interfaces and protocols)	• Upham et al. (2020), Greene et al. (2020); Asif and Schmidt (2021) • Leibowicz (2018); Pohl and Yarime (2012);Wu et al. (2021)

The diversity of potential barriers evoked by this four-dimensional view (Table 1) reflects the heterogenous character of the structural components that make up a technological innovation system (Bergek et al., 2015, Bach et al., 2021). Following the literature from this field (Suurs et al., 2009) along with socio-technical systems (Geels, 2004, Sandén and Hillman, 2011, Trencher et al., 2020a, Truong et al., 2022), the technological innovation system supporting road transport can be conceived as an interconnected web of physical artefacts (e.g. technologies, parts, materials, infrastructure), human actors (e.g. firms, organisations, policymakers) and capital alongside non-material aspects like economic or social forces and institutions (e.g. laws, regulations). In this systemic view, technologies do not exist independently in a 'vacuum', but rather, form part of a broader, interconnected and complex social system. Thus, in the case of an emerging mobility technology like BEVs or FCEVs, the speed of production and diffusion is strongly influenced by the dynamics shaping the wider socio-technical configuration (Rietmann and Lieven, 2019, Koasidis et al., 2020).

A key feature of these dynamics are the interactions that arise between the interconnected elements of the market (Kieft et al., 2017, Seto et al., 2016, Wieczorek and Hekkert, 2012). Given the heterogeneity and complexity of innovation and socio-technical systems, interactions can be uni-directional (where one component influences another) or bi-directional (where two components mutually influence each other). They can also unfold at different scales (Turner et al., 2016, Aminoff and Sundqvist-Andberg, 2021). Furthermore, feedback loops arise when two or more components share a self-reinforcing relationship. In the case of positive feedback loops, these will drive system development, becoming so-called 'motors of innovation' (Suurs, 2009). Conversely, negative feedback loops will hamper the formation of technological systems (Wesseling and Van der Vooren, 2017, Janipour et al., 2020).

The systemic perspective described in socio-technical and innovation systems literature has inspired the approach of numerous transport scholars (Truong et al., 2022, Koasidis et al., 2020, Struben and Sterman, 2008, Klitkou et al., 2015). In particular, Greene et al. (2020) underscored the interdependent and co-evolutionary character of hydrogen mobility systems. This is best captured by the oft-cited 'chicken or egg' situation, where vehicles cannot be produced or bought until supporting infrastructure is in place, and infrastructure cannot attain profitability until enough vehicles are in circulation (McDowall, 2016). This particular situation indicates a barrier, which impedes the diffusion of an electric drivetrain technology. However, interactions can also be positive, propelling market creation by design or chance. For example, increasing the availability of charging or refuelling stations can increase consumer willingness to adopt electric drivetrains, thereby inciting supply-side investments in vehicle production, which then drives technological progress and cost reductions (Greene et al., 2020). These interlinked dynamics illustrate the need for a systemic understanding of mobility markets, since mutually reinforcing interactions, whether driving or hampering, will occur between the different dimensions and components of the system (Struben and Sterman, 2008).

Central to this picture is the concept of a 'systemic barrier' (Klein Woolthuis et al., 2005).[1] This refers to the negative attributes of

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[1] The notion of a 'systemic barrier' receives various labels in the literature, such as 'system failures' (Klein-Woolthuis et al., 2005), 'systemic problems' (Negro et al., 2012) and 'systemic imperfections' (Van Mierlo et al., 2010).

any component, function or interaction that impairs a system's development along with the production or diffusion of innovation (Carlsson et al., 2002, De Oliveira et al., 2020). From a structural perspective, the emergence of a socio-technical system can be hampered if a component – be this technology manufacturers, knowledge sharing networks, investments or infrastructure – is missing or too small. Conversely, a component may exert a negative impact on another, thereby creating a functional problem. In other words, systemic barriers compromise the optimal growth and functioning of a system, blocking the motors of innovation (Suurs, 2009). For this reason, systemic barriers are commonly referred to as 'blocking mechanisms' (Bergek et al., 2008, Kieft et al., 2017, De Oliveira et al., 2020). Moreover, because of mutual interactions across components, one systemic barrier can create or reinforce others within a system (Wesseling and Van der Vooren, 2017, Turner et al., 2016, Kieft et al., 2017).

This systemic view has inspired a burgeoning field of empirical work. Many scholars have diagnosed systemic barriers through a triple process of identifying: (i) system components and problems, (ii) interactions, and (iii) feedbacks and self-reinforcing blocking mechanisms (Kieft et al., 2017). Moreover, though this view is particularly prevalent in transport literature, systemic barriers have been identified in diverse contexts including agriculture (Turner et al., 2016, Sixt et al., 2018), construction (Wesseling and Van der Vooren, 2017), renewable and fossil energy (Negro et al., 2012, Trencher et al., 2020a, Mäkitie et al., 2018), housing construction (Kieft et al., 2017), heavy industry (Janipour et al., 2020) and waste treatment (Aminoff and Sundqvist-Andberg, 2021).

The investigation of systemic barriers is not a purely theoretical pursuit. Rather, empirical findings can inform innovation policies. That is, thanks to their linkages with multiple areas in a technological system, systemic problems provide an attractive leverage point for policy interventions aimed at correcting system performance (Kieft et al., 2017, Wieczorek and Hekkert, 2012, Wesseling and Meijerhof, 2021).

2.2. *The relative nature of barriers*

As the above approach to identifying systemic barriers has proliferated across various strands of literature, transitions scholars have tended to focus on single technological innovation systems. Though recent work is increasingly addressing this limitation (e.g. Raven and Verbong, 2007, Geels, 2018, Ulmanen and Bergek, 2021, Wesseling et al., 2021, Andersen and Markard, 2020), by and large, studies have frequently overlooked the impact of one technology or socio-technical system on another by omitting exogenous context when fixing analytical system boundaries (Bergek et al., 2015).

To avoid this tendency in the prior literature, this study works with the idea that the hampering effect of systemic barriers is defined not only by their absolute nature, but equally by their *relative* nature. That is, we postulate that stakeholders frequently perceive an internal barrier in a socio-technical system (e.g. the high cost of technology X) in relation to factors outside that system (e.g. the cost of technology X compared to technology Y). Thus, for our empirical cases, we expect barriers to simultaneously encompass an absolute and relative character. This means that not only will barriers exist in an absolute sense because of internal conditions within the FCEV market, but we also anticipate their hampering effect will be magnified by their relation to external factors. These include the performance of other niche technologies like BEVs, as well as established technologies like internal combustion engine vehicles.

This idea rests on descriptions of dynamics arising from competition between technologies in economics and innovation literature (David, 1985, Suarez, 2004). The concept of a 'dominant design' is particularly pertinent (Utterback and Suárez, 1993). Such work describes how in new or transitioning industries, different technologies compete to become the new de facto standard. Dominant designs emerge because they provide compatibility, networking and scaling benefits. As Arthur (1989) showed, this holds particularly for technologies whose attractiveness increases with adoption, like phones and infrastructure-dependent technologies.

Transport scholars frequently discuss competition across different electrification and decarbonisation technologies (Sandén and Hillman, 2011, Phirouzabadi et al., 2020b). Some have adopted a systems perspective (Hekkert and van den Hoed, 2004, Churchman and Longhurst, 2022), attempting to forecast the dominant design that will replace internal combustion engines. Differing low-emission propulsion choices besides fuel cells include not only niche technologies like batteries and biofuels, but also more established technologies like hybrid drivetrains. As a result of this multiplicity of options, automakers and policymakers can find themselves faced by a dilemma about which to support with their limited resources (Köhler et al., 2013, Budde and Konrad, 2019). Competition from batteries is especially relevant for hydrogen. With both technologies providing a zero-emission solution for drivetrains, many scholars view FCEVs as battling with BEVs for sales, automaker investments and policymaker support (Van de Kaa et al., 2017, Ajanovic and Haas, 2019).

While researchers tend to work with the idea of competition across emerging technologies and the eventual domination of one (Utterback and Suárez, 1993), in many cases a mobility transition (and indeed other kinds of socio-technical transitions) will involve the parallel development of multiple niche-innovations (Geels, 2018). That is, several technologies can co-exist and contribute to the decarbonization of the dominating socio-technical system, such as mobility. But as long as multiple powertrain technologies exist in the same market, the presence of one option is expected to impact another (Sick et al., 2016). This can result in both driving and hampering effects (Phirouzabadi et al., 2020b, Dijk, 2014). For instance, two alternative technologies can attain a symbiotic relationship, whereby the emergence of one assists the development of another. This is the case with BEVs and hybrids, since both technologies draw on electric motor and battery technologies. Conversely, two technologies may exist in a competitive relationship, where the emergence of one, like battery drivetrains, erodes the market potential for another, like hydrogen or biofuels (Mutter, 2019). Furthermore, these relationships can change overtime, following the development trajectories and market penetration speeds of differing mobility technologies (Phirouzabadi et al., 2020a).

In sum, the relative dimension of barriers and competing technologies helps to enrich understanding of the diverse factors that we expect to hamper the emergence of FCEV markets.

3. Methods

3.1. Study design and case selection

This study employs a qualitative and comparative research design to elucidate the factors impeding FCEV adoption in key markets. As already noted, three cases were selected for this objective: California, Japan and Germany.

Multiple reasons underpin their selection. First, the collective efforts in each market by government, industry and research institutions are widely regarded as strategically important for global efforts to accelerate the production and diffusion of mobile and stationary fuel cells and hydrogen (IEA, 2019, Delloitte, 2020). Second, each case provides a contrasting representation of important variables. Asides evident differences in terms of culture, geography, politics, language and history, Germany and Japan are both global automotive superpowers that have engaged in the development of FCEVs since the late 1990 s (Ehret and Dignum, 2012, Ishitani and Baba, 2008). For policymakers, efforts to spur the diffusion of FCEVs in Germany and Japan are thus driven by ambitions to spur the emergence of a globally competitive fuel-cell industry (Behling et al., 2015, Budde and Konrad, 2019). In contrast, California lacks a domestic FCEV-making industry. Its ambitions to spur the diffusion of FCEVs are principally environmental (Trencher et al., 2021). Propelled by the historical mission of cleaning up chronic air pollution (of which road transportation is the major source), policymakers have wielded stringent command-and-control policies to pursue this goal (Collantes and Sperling, 2008, Sperling and Nichols, 2012). We thus expect these contrasting market characteristics to reveal diverse conditions affecting FCEV diffusion across the globe.

3.2. Scope and data sources

This study focuses specifically on passenger FCEVs (i.e. light-duty) as opposed to buses and trucks (i.e. medium or heavy-duty). Between January 2018 and January 2021, FCEV markets in California, Japan and Germany were studied individually, resulting in three publications (Trencher and Edianto, 2021, Trencher, 2020, Trencher et al., 2020b). This study draws on this past research to extract new insights by comparing experiences across countries. Follow-up data collection was carried out for this purpose in 2021, from October to December.

This resulted in a dataset assembled from 59 semi-structured interviews (both face-to-face and online), diverse documents (academic studies and grey literature, such as policy documents, reports by government, industry and research institutes and web pages) as well as notes drafted when participating in workshops and symposiums.

The interviews targeted diverse practitioners in government and industry (e.g. vehicle makers, fuel suppliers, industry organisation, consulting firms and policymakers) along with researchers in universities and research institutes (see Appendix A Tables 1-3). Earlier interviews focused on the strategies used in each market to accelerate FCEV deployment, but also discussed hampering factors. In contrast, follow-up interviews focused exclusively on barriers. Despite the slightly differing objective, all interviews shared the common approach of inviting respondents to freely articulate governance strategies and barriers from the four perspectives outlined in the analytical framework (Table 1). Most interviews did not pre-define barriers and simply asked, for example: ‘In your view, what are the main barriers hampering the supply of FCEVs?’ While this approach allowed respondents to freely describe obstacles they deemed important, some interviews probed about the existence of a specific barrier observed in another market. All interviews were recorded and fully transcribed.

3.3. Data analysis

Transcripts and documents were coded with software (MAXQDA). This applied each dimension in the framework (Table 1) as priori codes (e.g. ‘vehicle production’) while iteratively creating open codes (e.g. ‘station equipment breakdowns’) to capture more specific descriptions of barriers.

Analysis of the coded data then proceeded in two steps. First, we identified and aggregated common and unique barriers from each market. Since the longitudinal dataset reflects experiences accumulated over several years, when identifying and discussing barriers we focus on those: (i) historically occurring, (ii) still occurring at the time of writing, and (iii) reported across multiple interviews or data sources.

The quantity and diversity of evidence created a need to systematically deal with differing and sometimes conflicting views over: (i) the existence of a barrier, and (ii) the magnitude of its negative impact. We overcame this twofold challenge by classifying the ‘hampering effect’ of barriers as follows:

- *Strong:* Barrier mentioned in multiple (≥2) sources of evidence and explicitly described as hampering development of the FCEV market. No or few conflicting views observed.
- *Weak:* No recurring mentions of barrier found. No conflicting views observed.
- *Uncertain:* Existence of barrier reported. But conflicting views observed in multiple sources (≥2) about the barrier's hampering effect on the FCEV market.

In the second step, we aggregated findings from the first step to identify causal relationships between barriers. This took inspiration from innovation systems research (Wesseling and Van der Vooren, 2017, De Oliveira et al., 2020) and approaches to building causal loop diagrams (Jiren et al., 2020, Dangerfield, 2020). Concretely, this involved first mapping out the commonly emphasised barriers in each market in accord with the four-dimensional framework and subsequently adding stakeholder explanations about 'what caused what' to illustrate relationships between barriers (Kieft et al., 2017). We also added causal relations that could be identified by logically assembling different descriptions (i.e. textual fragments) about barriers from interviews and documents (see Supplementary Material). Rather than visualising the entirety of specific circumstances that characterise each market, the causal loop analysis focused on adding the principal barriers and interactions reported across all cases. This proceeded until a satisfactory level of saturation was achieved. Care was taken to avoid adding too many factors (Jiren et al., 2020), since this would increase the diagram's complexity, reducing its value for providing a concise overview of the principal dynamics and systemic barriers shaping each market. Lastly, we verified our interpretations by sending the resulting visualisation (Fig. 1) to stakeholders, then making changes based on feedback.[2]

4. Introduction to the cases

Each market is growing at a different speed. Table 2 summarises the state of vehicle and refuelling stations deployment along with future targets. The inclusion of global data and BEVs helps to contextualise each market's scale. California has the largest fleet, with around 10,127 FCEVs registered in December 2021. However, this fleet is dwarfed by the roughly 21 million light-duty vehicles (non-ZEV) registered, and the stock of nearly 825,000 plug-in electric vehicles (CEC, 2022). California's refuelling infrastructure is also comparatively underdeveloped, having only 56 retail stations in operation. Conversely, Germany has a nascent fleet of vehicles, with less than 1,600 registered as of June 2022. The ratio of vehicle to refuelling stations thus varies highly across markets. In the case of California, each refuelling station serves on average 181 FCEVs, indicating that a small number of stations are supporting a large number of vehicles. Conversely, the 95 or so refuelling stations in Germany have only 17 vehicles each as potential customers. As we discuss later, these varying ratios have implications for vehicle diffusion and station profitability in each market.

Additionally, the contrasting intensity of ambitions to further expand each market sheds important hints into future growth potential for hydrogen passenger mobility. The target of scaling Germany's refuelling network up to 300 stations by 2030 was once conditional, depending on the number of on-road vehicles in coming years. In early 2022, however, H2 Mobility (an industry platform charged with refuelling network planning, financed by fuel suppliers and automakers) formalised a commitment to achieving this goal regardless of present on-road vehicle numbers (H2Mobility, 2022). Meanwhile, the Japanese state has fixed a goal of reaching 800,000 FCEVs by 2030 and expanding the current refuelling network to 1,000 stations (METI, 2017). This same target is shared by industry and government in California alongside a larger goal of reaching 1 million on-road vehicles by 2030 (CARB, 2021a). These targets suggest that government and industry in California and Japan are relatively optimistic and committed to growing the FCEV market

Table 2
Key indicators of market scale for cases.

	Current				**2030 target**		
	Germany	**Japan**	**California**	**Global**	**Germany**	**Japan**	**California**
FCEVs (on-road)	1,611	~6,710	10,127	~43,000	none	800,000	1,000,000
Refuelling stations (operating retail)	95	160	56	~530	300	1,000	1,000
FCEV to station ratio	17:1	42:1	181:1	79:1	n/a	800:1	1,000: 1
BEVs (for reference)	753,489	281,350	827,760	~11 million	15 million	None	5 million

Notes: Figures for 'on-road' vehicles indicate still active registrations. The number of refuelling stations in Japan includes truck-based mobile stations. BEVs data includes plug-in hybrids. BEV targets are assumed to include plug-in hybrids and FCEVs.
Data sources: *Germany:* FCEVs and BEVs from National Organisation Hydrogen and Fuel Cell Technology (NOW, 2022) and refuelling stations from H2 Mobility (2022) for June 2022. BEV target for 2030 (Reuters, 2022). *Japan:* Refuelling stations from JHyM with figures for June 2022; FCEVs from IEA (2022a) for end of 2021; 2030 targets from METI (2017); BEVs from Next Generation Vehicle Promotion Center for end of financial year 2020 (March) (NEV, 2021). *California:* FCEVs from California Energy Commission (2022) for end of 2021; refuelling stations from California Fuel Cell Partnership (2022) for June 2022; 2030 targets from California Air Resources Board (2022). BEV target for 2030 (GO-Biz, 2021). *Global:* FCEVs and BEVs from IEA (2022b) for June 2021.

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[2] Concretely, we received suggestions for marginal changes from four stakeholders.

compared to Germany. This commitment remains despite missing historically set targets such as 40,000 FCEVs by the end of fiscal year 2020 in Japan (METI, 2017) and 68 operating refuelling stations by 2016 in California (CFCP, 2012). Finally, if comparing Japan's situation to Germany and California, the lack of an explicit diffusion target for on-road BEV numbers in 2030 indicates that in Japan FCEVs rather than BEVs have tended to feature at the forefront of zero-emission vehicle discussions, alongside hybrids.

5. Findings

5.1. *Analysis: Identification of barriers*

This first part of the findings discusses the most important barriers identified in each market, structuring the analysis in accord with the four-dimensional framework. Tables 3-6 summarise the main barriers for each market, also rating their hampering effect following explanations in Section 3.3. Supporting evidence in the form of illustrative quotations from interviews are compiled into Supplementary Material. Hereon, codes in brackets refer to anonymised interview sources (G = Germany, J = Japan, C = California).

5.1.1. *Vehicle production*

Low supply of vehicles and models

A limited supply of vehicles and automakers mass-producing FCEVs has inhibited the growth of each market.

Numerous stakeholders in Germany, Japan and California conveyed a historical optimism that automakers previously active in the development of FCEV prototypes would follow through on commercialisation plans. Over the past two decades, such automakers included Volkswagen and Daimler in Germany, Ford and GM in the United States, and Honda, Nissan and Mazda in Japan (Ishitani and Baba, 2008, Ehret and Dignum, 2012, Budde et al., 2012). But these players have since abandoned or postponed ambitions to commercialise FCEVs, instead focusing light-duty electrification strategies on batteries. Germany's situation is particularly chronic, since no domestic automaker currently produces FCEVs for the mass-market. BMW plans to release an SUV during 2022, albeit in limited volume, while Audi is rumoured to be considering production (G:2,3,9). In Japan, Toyota and Honda are the only domestic automakers serially producing FCEVs over the past five or so years. Toyota has maintained its commitment to mass-producing its *Mirai* sedan, building a specialised factory capable of manufacturing up to 10,000 annual units. But prospects for a larger supply of FCEVs in Japan dimmed after Honda announced in 2021 it would suspend production of its *Clarity* for an unspecified time period (Omoto, 2021). In California, since no American automaker has yet commercialised an FCEV, supply has depended entirely on imported vehicles from Japan and Korea. This volume, however, has constantly been below the expectations and predictions of government and industry (CARB, 2021a) (C:10,11).

Besides the stagnant supply of vehicles per se, the lack of diversity in models has also hampered market growth, since limited vehicle choices have reduced the appeal of FCEVs to broad user segments (Hardman and Tal, 2018) (G:9; J:13,14; C:19). This has been especially problematic in Japan, where until Hyundai's SUV entered the market in early 2022, model choices were limited to sedans from Toyota and Honda.

Table 3
Vehicle production barriers hampering development of the FCEV market.

Barrier	Germany	Japan	California	Details and interview or document sources
Low supply of vehicles and models	*Strong*	*Strong*	*Strong*	• All markets: Supply of vehicles constrained by the lack of domestic automakers producing FCEVs and limited supplies from overseas makers (G:1,8–13; J:2,4,6,12,13,16,19–22; C:10,16,19) (CARB, 2019, CARB, 2020). • All markets: Multiple automakers previously developing FCEVs have postponed or abandoned commercialisation plans (G:2,5,6; J:13,21; C:10,20) (Murasawa, 2022).
Technological difficulties	*Strong*	*Strong*	*Not examined**	• Germany and Japan: Technological complexity of fuel cells and hydrogen tanks hampers mass production abilities and new entrants (G:1,8,10–13; J:6,12,13, 20–22).
High cost of vehicle and component production	*Strong*	*Strong*	*Not examined**	• Germany and Japan: High cost of producing components and FCEVs relative to BEVs hampers production motivations for existing automakers and potential new entrants (G:2,9,11,13; J:1,6,13,16,19,21,22).
Time and difficulty of establishing part supply chains	*Strong*	*Strong*	*Not examined**	• Germany and Japan: Ability for vehicle makers to produce FCEVs is constrained by the time and difficulty of setting up part supply chains (G:4–6; J:6,21).

* **Note:** Production related barriers were not examined for California due to the absence of locally based FCEV production.

The sparse supply and diversity of vehicles in each market can be largely explained by slow and cautious investments by automakers and a tendency to favour BEVs when building ZEV powertrains and production capacity (G:11; J:13,19; C:14). Moreover, as discussed below, this situation is especially the result of relative barriers – namely technological complexity, production costs, and challenges with setting up part supply chains – which are all higher than for BEVs.

Technological difficulties

Several industry practitioners and experts in Germany and Japan echoed a view that the innate technological complexity of FCEVs – namely fuel cells stacks and tanks – has hampered production efforts. This has inhibited existing FCEV makers as much as discouraging the emergence of new entrants (Murasawa, 2022). Conversely, technological hurdles when mass-producing BEVs are comparatively lower, since fewer components are involved, and plentiful opportunities exist to procure these on the open market (G:14; J:12). Indeed, as one automotive stakeholder in Germany described: 'The fuel cell is not the technology that you can implement tomorrow. Toyota has more than 20 years of development expertise, and Hyundai as well [...]. The entry is easier for battery electric vehicles than for fuel cell electric vehicles' (G:12).

Technological difficulties arise from several aspects. Fuel-cell applications in passenger cars were widely described as immature relative to batteries (G:2; J:21). Automakers in Germany and Japan are still contending with technological challenges. These include how to ensure the long-term durability of fuel cells and smooth functioning in extreme cold (G:13; J:7), as well as how to cheaply mass-produce fuel tanks that can withstand high pressures and meet safety standards (J:21). These difficulties have damped ambitions to rapidly upscale production for fear of provoking technological defects that would require an expensive and reputation damaging recall (G:10; J:21). Acknowledging these challenges, several experts (J:12,20,21) shared a view that unanticipated technological problems have influenced Honda's abovementioned decision to suspend production of FCEVs.

In comparison, the technological simplicity and rapidly improving performance of batteries were described as providing 'the (electrification) path of least resistance' for automakers (C:14). Relatively lower technological hurdles for BEVs have thus induced larger and sustained investments by automakers, particularly in Germany (G:2,14).

Higher cost of vehicle and component production

The relatively higher costs involved in mass-producing FCEVs has also dampened automaker appetites for investing in hydrogen.

In addition to the above-described technological complexity of fuel cells (Asif and Schmidt, 2021), elevated costs result equally from challenges related to their mass-production. The latter task involves a need to grapple with trade-offs between production speed and technical reliability. But German automakers have especially been unwilling to make large investments in automated production lines capable of achieving both speed and precision (G:11). Further elevating costs, FCEVs require expensive materials such as platinum for fuel cells and carbon fibre for fuel tanks. In addition, since production volumes of all makers remain limited, automakers have been unable to attain economies of scale. In the case of Japan, high production costs have induced the production of luxury sedans, where cost recovery is easier. But their high retail tag has reduced the attractiveness of FCEVs to mass-market consumers (J:2,21). To cut the costs of fuel-cell production, industry and government in Japan and Germany are concentrating efforts on reducing platinum requirements and increasing power density.

Despite these efforts, multiple stakeholders pointed to faster learning curves in the battery-mobility market by virtue of its greater scale, arguing that the lower costs needed to produce vehicles are inducing larger and growing investments (C:20; J:13; G:2,9,11). Indeed, building a mass-production capability for FCEVs would cost 'one billion euros' explained one automotive stakeholder in Germany; 'So why spend another billion if we still haven't done our homework on electric cars?' (G:11).

Time and difficulty of establishing part supply chains

Evidence from Germany and Japan (G:4–6; J:6,21) indicates that the lengthy periods required to set up component supply chains have also shackled the ability of automakers to enter the FCEV market or upscale production. Even when making fuel cell stacks and tanks in-house, serial production of FCEVs still requires complex negotiations and logistical planning with upstream suppliers to secure components like air pumps, fuel injectors, fuel leak sensors, etc. As an industry practitioner in Japan described, until recent investments by Toyota and Honda, 'there was no supply chain or market [for the necessary components]' (J:21). Describing how the same situation had stalled serial production plans for automakers in Germany, one industry expert explained: '[...] from the drawing board to mass-production at a good price you might need 10 years' (G:5).

Though several years are also required to secure reliable supply chains for BEV components, once again, barriers in this market were perceived as lower, mainly because of plentiful part suppliers and comparatively fewer components used in vehicles (G:14; J:21,12).

5.1.2. Infrastructure barriers

Availability of stations

Despite governments resolving to deploy stations before vehicles, the limited availability of refuelling infrastructure is impeding each market's development.

Table 4
Infrastructure barriers hampering development of the FCEV market.

Barrier	Germany	Japan	California	Details and interview or document sources
Availability and capacity of refuelling network	*Strong*	*Strong*	*Strong*	• All markets: Limited station numbers and locations pose driver inconveniences, reducing the attractiveness of FCEVs along with demand (G:13,17; J:1,8,12–14,20,21; C:10,19) (Kelley et al., 2022, CARB, 2021a, Lopez Jaramillo et al., 2019). • All markets: Limited refuelling coverage prevents automakers from supplying more FCEVs to market (G:1–3, J:11; C:1,13,14,16). • Germany: Station network stops at border, preventing international travel, thus hampering demand (G:3,9,11).
High cost of station construction and operation	*Strong*	*Strong*	*Strong*	• All markets: High cost of station construction and operation impedes profitability, discouraging further investments to expand the refuelling network (G:4,3,12,15,17; J:7,11,19–21; C:19,22) (CFCP, 2018). • All markets: Construction and operation costs exacerbated by low economies of scale and hampering or sub-optimal regulations (G:4,15; J:7,13,19,21; C:11,13).
High cost of fuel	*Strong*	*Strong*	*Strong*	• All markets: High fuel costs hamper profitability for station operators (G:15, J:11; C:8). • All markets: High fuel costs relative to BEVs reduce the attractiveness of FCEVs for business fleets (G:12, J:4,14) and mass market adopters (J:1,21; C:1,11,20) (CARB, 2021a, CARB, 2021b). • California: The need for automakers to supply free fuel to stimulate demand reduces the financial incentive to rapidly increase vehicle supplies (C:9,20).
Low profitability of stations	*Strong*	*Strong*	*Strong*	• All markets: The low number of on-road FCEVs causes stations to run at a loss due to low fuel demand. Uncertainty over future profits supresses investment in additional stations (G:2,4,10,12,17; J:2,4,6,7,11–13,19–21; C:11,13,19,22)
Poor reliability of stations	*Weak*	*Uncertain*	*Strong*	• California: Equipment breakdowns and fuel shortages frequently occur, bringing stations offline for extended periods. This creates negative driver inconveniences, damaging public reputation of FCEVs (C:3,6–8,10,13,17,22) (Kelley et al., 2020, Lopez Jaramillo et al., 2019, CARB, 2021a, CFCP, 2018, Kurtz et al., 2019). • Germany and Japan: Equipment breakdowns and fuel shortages not frequently reported. Most breakdowns occur in older stations (G:1,5,6,8,15; J:13,14,20).

California has the smallest fleet of operating stations, currently 56 as of June 2022 (Table 2). Not only is this considerably below the original target to reach 68 stations by 2016 (CFCP, 2012, Kang et al., 2014), drivers are heavily inconvenienced by the underdeveloped network, frequently having to queue in front of stations during busy refuelling periods. Germany and Japan have comparatively more stations (95 and 160 respectively), and queues seldom occur, since vehicle to station ratios are lower than California. But in all markets, coverage is insufficient to drive demand for FCEVs. Germany's situation is exacerbated by the need to build a network in neighbouring countries, to permit travel around Europe (G:3,6,11). Meanwhile, stations in both Japan and Germany tend to feature in peripheral or industrial locations, isolated from downtowns.

This situation has impeded market growth in two ways. First, by creating actual or perceived inconveniences for drivers, it has supressed demand for vehicles. Second, multiple industry and government stakeholders echoed a view that the limited availability of refuelling infrastructure has also influenced decisions by German, Japanese and Korean automakers to abandon or delay plans to either enter the FCEV market or upscale their vehicle production volumes. Meanwhile, the comparatively wider availability of recharging infrastructure for BEVs and lower hurdles to installation has attracted greater investments in vehicle production by automakers, also enjoying firmer support from some policymakers (G:2,3,9;11; C:1,14,15).

Cost of station construction and operation

In each market, the elevated costs of building and running stations are impeding efforts to expand refuelling networks. Moreover, this barrier is occurring despite government support for construction costs, covering around 50 % in each market, and revenue support mechanisms in Japan and California. In Japan, new construction costs are particularly problematic, averaging around JPY 350–400 million[3] over 2016–2021 (Yomiuri Shinbun, 2021, METI, 2019). Excluding land acquisition, this cost of purchasing and installing equipment is roughly two to three times higher than Germany and California. But operational expenses also hamper infrastructure development. Principally incurred when procuring fuel and operating or maintaining equipment, such operational overheads far exceed construction costs over an average station's lifetime (CARB, 2021b). Operational hurdles are particularly problematic in Germany, since government support for infrastructure deployment is limited to construction costs (G-4).

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[3] Approximately US $2.88 to $3.29 million on March 25, 2022.

Cost hurdles arise from two common causes. First, the limited number of stations in each market prevents economies of scale for planning, building and operation (G:4; J:19,21–22; C:9,18). Not only does this hinder cost reductions in equipment manufacturing and installation, but scalability is also lost when transporting, storing and dispensing hydrogen due to the limited capacity of stations and fuel sales. Decreasing these costs requires more and larger stations, higher volumes of fuel sales, and optimized fuel delivery networks, since truck delivery prices fall as scale increases (C:8). Second, sub-optimal institutional environments also cause extra costs during infrastructure development. Detailed in Section 5.1.4, this issue relates especially to restrictive or overly prescriptive safety and permitting procedures along with station operation protocols.

High cost of fuel

Each market shares a pressing need to lower the production and retail cost of hydrogen fuel (Vijayakumar et al., 2021, Upham et al., 2020, Trencher et al., 2020b). Industry and Germany and Japan have fixed an artificial price ceiling. This sets retail costs to EUR 9.50 and JPY 1,100[4] per kilo, achieving running cost parity with diesel and hybrid vehicles, respectively. While this hides the real cost of hydrogen production from consumers during the early FCEV adoption phase, industry must shoulder the lost retail margin. California, meanwhile, sells hydrogen at actual market prices. Pump prices are consequently the highest of the three markets, retailing for around US $16 per kilogram in 2021 (CEC & CARB, 2021).[5]

Two principal causes underly high fuel costs. The first is production per se, since the scale of hydrogen produced in accord with the purity requirements of transport applications in each market is low. The second cause is delivery. With most hydrogen delivered by truck, each market shares a pressing need to lower delivery costs through technological improvement, like increasing the carrying capacity of tankers and, eventually, building alternative distribution networks such as pipelines (G:15; C:3). To overcome such barriers, Germany and Japan currently share a strategy that seeks to cut fuel costs by establishing large-scale supply chains – including efforts to import hydrogen mass-produced overseas (BMWI, 2020, METI, 2019). This strategy aims to attain economies of scale by coupling the mobility market with industrial applications.

High fuel costs are shackling vehicle demand for both private consumers and commercial applications (G:12; J:1,4,14; C:1,11,20). Furthermore, this barrier is exacerbated by the lower running costs enjoyed by BEVs. This relative disadvantage has particularly impacted the adoption of FCEVs in commercial applications, since businesses are particularly sensitive to running costs (G:12; J:4,14).

California's situation is unique, with negative consequences for both vehicle production and demand. Since hydrogen is retailed at market prices, FCEV running costs must compete with gasoline, which is artificially suppressed by fiscal incentives at the federal level (C:11,17,20). To create demand in such conditions, automakers have opted to supply free fuel with vehicles, covering up to $15,000 or 3-years. Yet this has eroded their motivation to rapidly upscale FCEV supplies to California, since each vehicle produced incurs losses (C:9,20) (CARB, 2021b).

Low profitability of stations

Stakeholders in each market bemoaned the low profitability of refuelling stations. In addition to high construction and operation costs, poor business performance essentially reflects the limited number of vehicles consuming hydrogen. The ratio of FCEVs to refuelling stations is currently 17:1 for Germany, 42:1 for Japan and 181:1 for California (Table 2). Accordingly, industry in Germany and Japan provided gloomy accounts of profitability. 'We are just doing this as a societal contribution', lamented one fuel supplier in Japan (J:11). Meanwhile, in Germany, descriptions of stations included 'cash burning machines', 'a rather mediocre business case' and 'totally pointless' (G:2,4,15). Moreover, because of the snail-paced growth of vehicle adoption in each market, uncertainty over future opportunities for profitmaking is supressing investments to add further stations.

Poor reliability of refuelling stations

California's refuelling network is contending with chronic reliability issues stemming from equipment breakdowns and fuel shortages (Kurtz et al., 2019, CARB, 2021a). Dispensers, and even entire stations, are frequently brought offline for several days, increasing pressure on the remaining stations to meet fuel demand. Breakdowns and malfunctions occur regularly in equipment such as compressors, refuelling dispensers and payment terminals (C:7,22). The technological immaturity of the refuelling industry is behind this, since limited station numbers have slowed learning, also hampering the formation of experienced manufacturing and maintenance networks (C:3). Fuel shortages also frequently arise because the hydrogen consumption of California's FCEVs fleet frequently exceeds the storage capacity of stations. The fragile nature of hydrogen supply chains also provokes fuel shortages. Concretely, distribution systems suffer from a limited number of hydrogen suppliers and truck delivery networks are frequently unable to keep up with fuel demand (C:8). Once again, such barriers were also described from a relative aspect, but this time regarding incumbent gasoline vehicles. One industry respondent described: 'The thing you're competing against is gasoline, and gasoline pumps are never down, right?' (C:3).

Station reliability barriers were not observed to the same extent in Germany and Japan, probably because utilisation rates are comparatively lower (J:21). Though breakdowns occasionally occur (G:1,6,15; J:20,21), their impact is far greater in California, since unpleasant driver refuelling experiences have triggered negative publicity and, in some cases, the abandonment of FCEV ownership (C:6,7,22) (CARB, 2021a).

5.1.3. Demand barriers

Weak demand for vehicles

Reports of low demand for FCEVs were observed in each market. The most visible indication of this is the limited uptake of vehicles

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[4] Approximately US $9.03 on March 25, 2022.

[5] A typical FCEV such as the Toyota *Mirai* can drive for about 100 km with each 1 kg of fuel.

Table 5
Vehicle demand barriers hampering development of the FCEV market.

Barrier	Germany	Japan	California	Details and interview or document sources
Weak demand for vehicles	*Strong*	*Strong*	*Strong*	• Germany and Japan: Most vehicle adoption to date is concentrated in corporations. Penetration into the mass market is slow, hampered by high vehicle costs, lack of models and limitations of the refuelling network (G:2,9,11,13–14,16; J:4,8,13,14,20–22; C:19) (Khan et al., 2021b). • California: Genuine demand for FCEVs per se is low, with sales heavily reliant on incentives such as free fuel (C:2,20,22; J:21).
Low visibility and public awareness of FCEVs	*Strong*	*Strong*	*Strong*	• All markets: The limited number of on-road FCEVs reduces their visibility, hampering public awareness and media attention (G:5,9,13,14; J:13,20,21; C:1,2,11,12,19,22) (CARB, 2021a, CARB, 2020, Lyons and Stewart, 2018). • Germany and California: Limited visibility negatively impacts political support.
Negative perceptions about environmental benefits	*Strong*	*Weak*	*Strong*	• Germany and California: Carbon emissions from fossil-fuel derived hydrogen and poor energy efficiency damage the reputation of FCEVs, affecting potential demand (G:5,14,16,17; C:10–14,19,22).

by individual customers in Germany and Japan. A web of forces was described by stakeholders as suppressing demand. Already discussed in earlier sections, this includes: (i) the high upfront cost of vehicles – even after government subsidies; (ii) the low availability of models; (iii) higher running costs from hydrogen; (iv) restrictions posed by limited refuelling networks; (v) and low attractiveness of vehicle design per se. Once again, stakeholders described these barriers as higher than for BEVs (G:2,11; J:8,20; C:19,22). Furthermore, stakeholders in Japan and California reported that many drivers have abandoned the technology, a principal cause being the limited or unreliable nature of refuelling stations (J:13; C:7).

Incidentally, though California enjoys the highest adoption of FCEVs in the three markets, some researchers claimed this does not reflect ‘real demand’ for vehicles per se (C:20). Rather, they claimed that most purchasers/leasers have responded principally to incentives like free fuel and access to high-occupancy vehicle lanes on expressways.

Low public awareness and visibility of FCEVs

Low awareness in the public space has shackled demand for FCEVs (Khan et al., 2020, Upham et al., 2020). Underlying this problem is the limited number of on road-vehicles, which hampers visibility of the technology. One industry expert in Germany asserted: ‘I would expect that the vast majority of the public is completely unaware of fuel cell passenger cars’ (G:5). Low public awareness of vehicles then exerts negative impacts on vehicle demand. A researcher in California explained this causality as: ‘If consumers aren’t seeing them on the roads […] why would somebody go out hunting for one?’ (C:22).

Interviews painted a contrasting picture for the BEV market, which enjoys a relatively greater degree of familiarity in the public realm. This has resulted from a virtuous nexus of forces that include the proliferation of vehicle chargers in high-visibility public areas like shopping centres; the success of Tesla in terms of vehicle sales, public recognition and attractive vehicles that standout on roads; a larger pool of BEV makers, models and on-road vehicles; and finally, wider coverage in the media (G:2,13,16; J:8,20; C:19,20,22). Conversely, public familiarity with FCEVs is eroded by a lack of high-visibility refuelling infrastructure (Knüpfer et al., 2021) and a smaller pool of automakers. Meanwhile, in Germany and California, FCEVs receive less media attention, mainly due to the lack of domestic manufacturers producing them. Besides, several industry and government stakeholders in each market concurred that vehicle demand is hampered by the lack of a ‘hydrogen Tesla’ (G:11; J:13; C:11). Though these stakeholders recognised that the attractiveness of Tesla’s vehicles per se have helped nourish demand for BEVs in general, they commonly expressed that FCEV market growth has suffered from the absence of ‘a major vehicle company with a very well-known leader who creates lots of publicity’ (C:11).

Negative perceptions about environmental benefits

Several stakeholders in California and Germany jointly conveyed concerns that negative perceptions about the environmental benefits of hydrogen are possibly reducing demand for vehicles. These issues were not observed to the same extent in Japan.

Negative public perceptions relate to three aspects. The first is CO2 emissions created from fossil-fuel derived hydrogen (Hardman and Tal, 2018). Though BEV recharging also creates upstream CO2 emissions unless electricity is sourced entirely from non-emitting sources, some stakeholders described hydrogen as more prone to public criticism about environmental benefits (C:12). A government bureaucrat in California explained (C:2): ‘I think sometimes that hydrogen seems to be criticized for several areas where maybe electricity markets or battery electric vehicle markets are not exposed to the same criticism.’ The second is that, unless produced from renewable resources, some critics see hydrogen as prolonging societal dependence on fossil fuels (C:12). Fuel sold in refuelling stations in both countries already contains a portion sourced from renewables – 28 % in Germany and 90 % in California[6] (H2Mobility, 2022, CARB, 2021a). Furthermore, not only is this share rising, industry and government are both working towards increasing the supply of renewable or low-emissions hydrogen in line with broader decarbonisation goals (G:4; C:11,13) (CFCP, 2018, BMWI, 2020). Nevertheless, the association between CO2 emissions, fossil fuels and hydrogen poses a significant barrier to social and political acceptance.

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[6] Hydrogen refuelling stations in California funded by the state government were previously required to provide a minimum 33% share of renewably sourced hydrogen. This target was raised to 40% in 2019. In addition, station operators voluntarily offset emissions. This resulted in an estimated statewide average of 90% renewable content for 2020.

A Californian researcher explained: ‘There’s a small segment of the population that is just extremely motivated from a green point of view. For them, it has to be zero emissions in the source of hydrogen and not just the tailpipe’ (C:19). Third, relative to battery pathways, the inferior energy conversion efficiency of hydrogen mobility (Upham et al., 2020) was also reported to tarnish perceptions about environmental merits of FCEVs (G:14; C:12,13,22).

Several German and Californian stakeholders also stated that demand for vehicles is possibly damaged by the circulation and magnification of such negative views through online and social media along with the discourse of critical political, academic and industry actors. Some claimed that the anti-hydrogen or strongly pro-battery positions of key environmental NGOs and the influential discourse of Tesla and Volkswagen have influenced the views of many potential adopters (G:15; C:11,13,22). Both automakers have issued public statements criticising the environmental benefits of hydrogen (Volkswagen, 2020, D’Allegro, 2019), while the latter has abandoned its historical efforts to commercialise FCEVs, choosing instead to concentrate on batteries. As a German stakeholder (G:14) explained: ‘If you read in the press every day that hydrogen is so inefficient, and that battery vehicles are the future to go, people get so confused’.

Incidentally, though hydrogen for transportation in Japan is similarly produced from fossil fuels, this was not perceived as a significant barrier. Reasons for this may include fewer critical views in media (probably because numerous Japanese corporations promote hydrogen) and because safety rather than environmental concerns are the focus of public acceptance issues (Khan et al., 2021a)(J:14).

5.1.4. *Institutional barriers*

Restricting or sub-optimal institutions

Market formation in each jurisdiction is suffering from sub-optimal institutions, such as local regulations, codes and protocols. Though differing in the details, these institutions share the feature of being overly restrictive and causing excessive costs for industry.

Problematic institutions have especially hampered the construction and operation of refuelling stations, notably in Japan. Industry here must contend with an outdated and excessively prescriptive high-pressure gas law. By regulating hydrogen under the same legal frameworks as other gases, refuelling stations must conform to safety requirements that are considerably steeper than in other countries. During construction, for instance, these raise costs by mandating durable and expensive materials along with safety features such as sprinklers, water tanks, rooves and concrete walls. These same legislations prevent station developers from importing cheaper equipment, since doing so necessitates an expensive retrofitting process to adopt components to Japanese standards (J:5,11,12,15,21). Japan’s institutional environment also raises operation costs by requiring two specialised staff onsite in each refuelling station and by mandating yearly maintenance shutdowns. The latter cost roughly between JPY 10–20 million[7] to implement, bringing stations offline for around two weeks (J:20). In California, institutional barriers mainly relate to the complexity and lengthiness of permitting procedures involved during station development. Different safety and zoning permits are needed from multiple local authorities. Not only has inexperience with permitting challenged industry and government alike, but each authority ‘has their own special rules’ (C:11),

Table 6

Institutional barriers hampering development of the FCEV market.

Barrier	Germany	Japan	California	Details and interview or document sources
Restricting or sub-optimal institutions	*Strong*	*Strong*	*Strong*	• Germany and California: Legislations fail to incentivise investments in large-scale production of renewable hydrogen (C:3,8,10,11,13) or raise costs for electrolytic hydrogen from renewable electricity (G:4,8,9,12,15). • California: Lengthy and complicated permitting procedures and local safety codes slow the construction of refuelling stations (C:11) (Greene et al., 2020, CARB, 2020, CARB, 2021a). • Japan: Strict laws and regulations raise constructions costs by requiring expensive compliance measures in refuelling stations (J:5,7,11,12,15,16,20,21) (Nagashima, 2020, Arias, 2019). • Germany and Japan: Environmental regulations have not forced the production or purchase of zero-emission vehicles (G:1,14; J:2,4,16,19,22).
Government support	*Strong*	*Weak*	*Strong*	• Germany and California: Political support for FCEVs has weakened, tilting towards batteries in the light-duty market and hydrogen in the heavy-duty market (G:1,4,6,8,10–12; J:21; C:1,10,11,13,16). • California: Federal policy discriminates against FCEVs, providing only consumer subsidies for BEVs (C:16) • California: Inconsistent funding for refuelling stations has hampered network growth until the establishment of a long-term funding scheme in late 2020 (C:8,10,14).

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[7] Approximately US $83,000 to $166,000 on March 23, 2022.

which have collectively raised costs and delayed station development (CEC & CARB, 2019, CEC & CARB, 2020). In the case of Germany, institutional barriers were raised with respect to sub-optimal refuelling protocols. Specifically, the mandatory pre-cooling margins set into hydrogen storage tanks are seen by some as unnecessarily raising the costs of construction and operation by assuming extreme temperature ranges beyond Germany's typical climatic range (G:15).

The *absence* of favourable institutions was also problematised in each market. In Germany and Japan, the lack of regulatory pressure (e.g. through zero-emission quotas for automakers or fleet operators) has contributed to the weak supply of FCEVs and their limited uptake in commercial fleets. Furthermore, in Germany and California, multiple stakeholders bemoaned the lack of government policies to incentivise investments in renewable hydrogen production. One German stakeholder (G:4) stated: 'I would love to source renewable hydrogen in Germany in large amounts. But the issue is that we don't have enough sources yet. It is not a business case to produce renewable hydrogen in Germany yet, because we have our EEG'. The described policy concerns an electricity surcharge of 6.5 cents/kWh that supports renewable energy diffusion. Raising the cost of green electricity, this institution has supressed investments into electrolytic hydrogen production. In California, likewise, stakeholders problematised the absence of institutions to incentivise utilities to provide electrolytic hydrogen projects with cheap electricity curtailed from renewables. Germany and California share a pressing need to solve these institutional roadblocks, since widely available and cheap, renewable hydrogen is essential for overcoming public acceptance issues.

Government support

In Germany and California, numerous stakeholders echoed a sentiment that political support for light-duty FCEVs has weakened relative to previous levels and the backing received by BEVs. This issue was not reported in Japan, where cooperation across government and industry to develop the hydrogen and FCEV market has seen less fluctuation (J:19).

Claims in Germany that state support has waned from historical levels have been influenced by the decision of key domestic automakers and trade associations to concentrate electrification portfolios on batteries rather than hydrogen. An automotive stakeholder (G:10) explained this causality as follows: 'Political willingness drops quickly if no European, especially if no *German* car manufacturer [emphasis added], is offering such vehicles on the market, because the German government has sometimes difficulty to argue why they spend so much funding money for not locally producing car manufacturers.' Conversely, some stakeholders claimed that political actors' preferences for batteries over hydrogen in the passenger market had contributed to automakers prioritising BEVs when formulating production plans (G:6,8).

Sentiments of weakened political support also surfaced in California. Industry and government stakeholders here cited lower funding volumes provided for refuelling infrastructure relative to that given to public vehicle chargers as a proxy for stronger support toward BEVs (C:1,6,12–14). Pointing to the sporadic nature and occasional absence of past government funding for refuelling stations, these stakeholders argued that 'political signals' regarding infrastructure development had negatively influenced the vehicle production plans of automakers (C:14). Meanwhile, as another indicator of inferior political support relative to batteries, some underscored the absence of purchase subsidies at the national level for FCEVs. Currently available only for BEVs, industry stakeholders claimed this institutional bias from Washington has slowed FCEV adoption (C:1,16).

5.2. Analysis: Identification of interactions between barriers

The preceding analysis highlighted multiple and persistent barriers hampering the growth of each FCEV market from the perspective of vehicle production, infrastructure, vehicle demand, and institutions. Several causal relations also came to light, illustrating the interlinked and systemic nature of these barriers. To better visualise these dynamics, this section briefly summarises several clusters of relations highlighted in Fig. 1.

First, each FCEV market is suffering from lost economies of scale in at least three areas (indicated with grey loops). One concerns the limited production of vehicles (blue boxes), which raises the cost of production per unit. This has a double consequence. On the one hand, the incentive for automakers to produce more vehicles is weakened. On the other hand, high production costs are passed onto consumers, reducing their attractiveness beyond a heavily subsidised niche market. Lost economies of scale are also impeding the development of refuelling networks (orange boxes). Largely a consequence of the limited number of refuelling locations in each market, this increases per-unit costs for planning stations, producing and installing equipment, and operation. Poor economies of scale also impact the supply of hydrogen to refuelling stations. While each country has large-scale gas producers, the transport market requires its own dedicated delivery systems, which at present, are predominantly truck-based. But the limited scale of this market has prevented significant cost reductions. Increasing the volume of vehicle and hydrogen supplies along with refuelling stations is the only way to overcome these cost related hurdles.

This, however, is hampered by other systemic barriers. Several self-reinforcing loops feature in these. For example, the limited production of vehicles is caused by multiple factors (see '1′ in Fig. 1). These include the technological complexity of mass-producing fuel-cell stacks and fuel tanks as well as difficulties in establishing supply networks for other specialised components. Together with the high costs required for production, these have raised market entry barriers for inexperienced automakers. As mentioned, these barriers are relatively lower in the BEV market, where fewer and less complex components are required, where economies of scale are higher, and where part suppliers are plentiful. Consequently, several automakers have scaled down or abandoned plans to commercialise

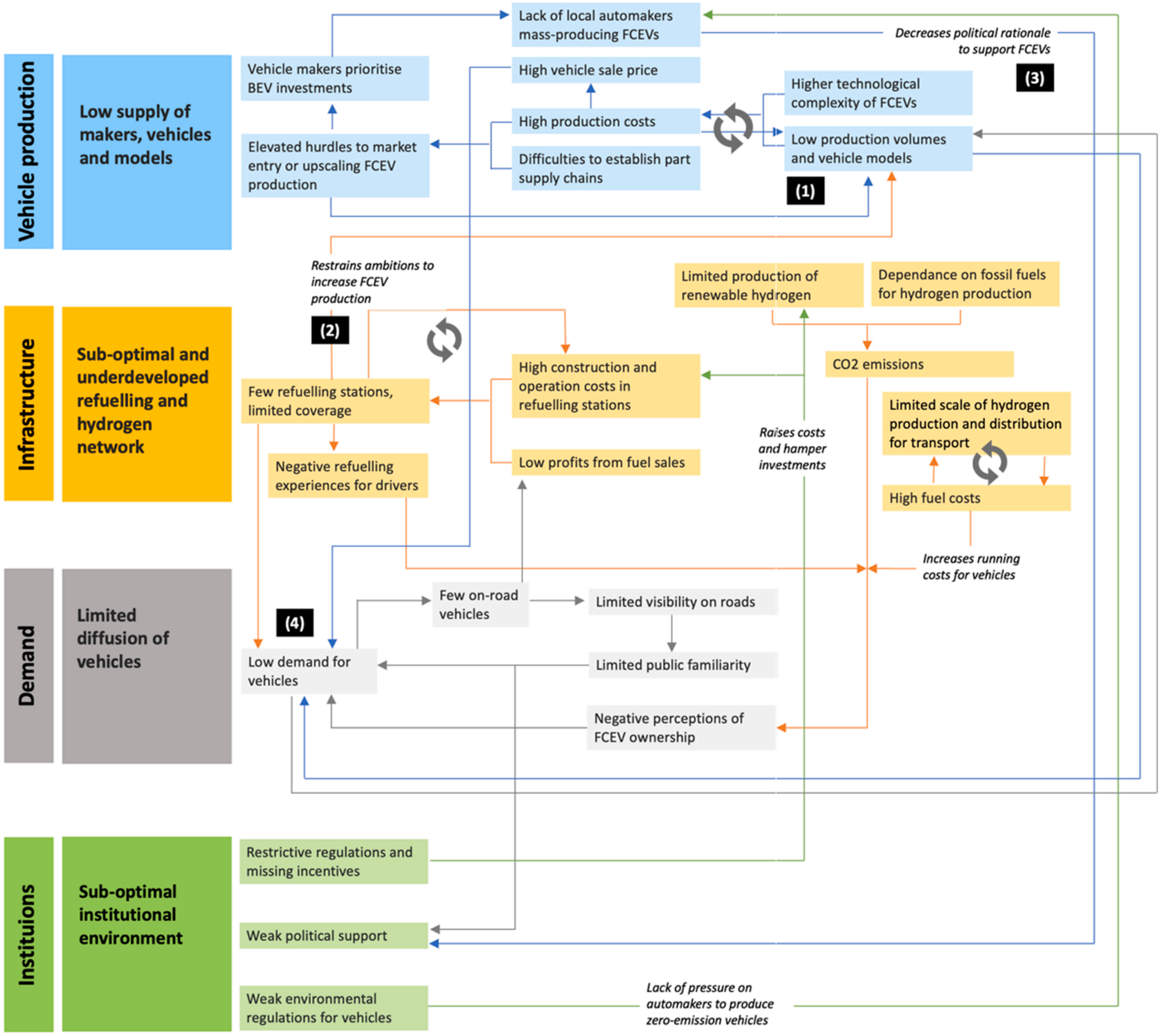

Fig. 1. Common systemic barriers observed across cases. **Note.** Figure shows main barriers observed in at least two of the three cases. Grey loop symbols show lost economies of scale driven by a reinforcing loop between low production volume and high costs. Figure is illustrative and does not display all possible barriers and causalities.

FCEVs, focusing their investments on batteries. A German automotive stakeholder elaborated this point: ‘Fuel cell electric vehicles are more complex [compared to BEVs]. But this is also an obstacle to us to invest into this technology because complex technology is expensive to develop’ (G:11). The low availability of stations has also shackled automaker intentions to produce vehicles at scale (‘2′ in Fig. 1). Because of these interlinked and self-reinforcing factors, each market’s supply of vehicles has been severely crippled relative to historical expectations by stakeholders and commitments from automakers.

This situation has then impacted other areas, notably institutional environments (green boxes) and demand for vehicles (grey). Negative consequences for the latter are self-evident, since demand can only grow as fast as the supply of vehicles. But more subtly, the stagnant state of vehicle production and lack of market entrants beyond BMW and Asian automakers has dampened political support in Germany and California (‘3′ in Fig. 1).

Finally, several barriers have hampered demand for vehicles (‘4′ in Fig. 1). These notably encompass a relative dimension. For instance, already discussed barriers like high vehicle costs, a lack of model choices, inconveniences from underdeveloped refuelling networks, concerns over CO2 emissions from fossil-fuel derived hydrogen and unfavourable running costs are all perceived in relation to BEV ownership.

In contrast, evidence from the three markets unequivocally suggests that BEV diffusion is currently propelled by virtuous loops in all four dimensions considered by the framework. That is, the supply of BEVs is rapidly growing as more makers and models enter the market. Increasing investments by automakers are propelled by rapidly improving cost reductions and economies of scale in production and fewer restrictions posed by infrastructure availability. In addition, rapidly improving driving ranges and charging speeds for batteries have eroded the comparative advantage of hydrogen for light-duty. The greater supply of BEVs along with low running costs has facilitated a virtuous cycle between increasing sales and demand, creating more public familiarity than for hydrogen. This has garnished political support in Germany and California, since politicians have supported batteries due to their larger societal visibility, technological improvements, lower barriers to infrastructure rollout, and moreover, the presence of local automakers, which creates an economic reason to support BEVs. In addition, for many automakers, the rapidly growing scale of the BEV market provides a safer business proposition than the niche market for FCEVs.

6. Conclusions and discussion

This study aimed to identify the principal barriers impeding efforts to upscale the deployment of passenger FCEVs in Germany, Japan and California. We adopted a systematic view, structured along four dimensions of market development: production of vehicles, infrastructure, demand for vehicles, and institutions. The findings revealed systemic and temporally persistent barriers in all dimensions. Collectively, these are hampering the mainstreaming of hydrogen as an electric mobility technology beyond the current niche market.

Moreover, findings revealed a host of linkages and self-reinforcing relationships across these barriers. As illustrated in Fig. 1, these are effectively slowing down the 'motors of innovation' (Suurs, 2009) in each FCEV market. For example, each market suffers from lost economies of scale in vehicle production, the construction of hydrogen refuelling stations and the production of hydrogen. Essentially, low production volumes raise per-unit costs, disincentivising private investments into the upscaling across the value chain so as to achieve cost reductions.

We also observed that for many stakeholders, the severity of these systemic barriers is compounded by their relative qualities when compared to the FCEV's direct competitor: the BEV. Over the past 10 years, BEVs have rapidly developed across all market dimensions, achieving larger economies of scale, radical cost-reductions, dense and widespread infrastructural coverage, and greater institutional support. For the FCEV market, this is leading to increasingly higher relative barriers, further slowing down the motors of innovation. In parallel, some of the historical and relative advantages of FCEVs – namely long driving ranges and rapid refuelling times – are declining as battery and charging technologies improve.

These dynamics paint a troubling picture for the global diffusion of passenger FCEVs, raising several questions for further research. In the longer term, are these barriers merely growing pains that will eventually be surmounted as FCEVs catch up to their BEV counterpart? After all, the complete electrification of on-road vehicles is expected to take several decades (Bento and Wilson, 2016, Hadjilambrinos, 2021), and the several years of experiences captured by this study capture only a limited slice of this long-term transition. Or is the idea of 'complementary' technologies in the passenger market no longer possible, with hydrogen poised to be muscled out of the passenger vehicle segment by the virtuous forces propelling growth of the BEV market? If this is the case, how will policymakers and industry deal with stranded investments made in hydrogen? And considering the merits of passenger FCEVs (e.g. suitability for long-driving ranges and large platforms as well as fewer needs for space-intensive charging infrastructure and critical minerals), would the loss of hydrogen in the passenger market slow down the speed of electrification in the road transport sector as a whole?

Our findings prompt several implications for scholars. Though literature has deepened understanding into the interconnected nature of systemic barriers, interactions between differing niche innovations and technological innovation systems are largely understudied. Recent work by scholars of innovation systems (Ulmanen and Bergek, 2021, Bach et al., 2021) and socio-technical transitions (Andersen and Markard, 2020, Geels, 2018) signals important progress in this area. Yet the relative nature of barriers to innovation and socio-technical change remains under-theorised (Hillman and Sandén, 2008, Penna and Geels, 2015). More research into such dynamics is needed, particularly to systematically compare interactions across different technological options, considering different contexts of competition and complementarity.

The analysis also shed important hints for decisionmakers in government and industry.

In all three markets, in the case that policymakers wish to keep FCEVs alive in the passenger segment, continued support for refuelling station operations is required until profitability occurs. Stronger incentives are also required to stimulate investments in renewable or carbon-free hydrogen production. In California and Germany, there is a need for strong and consistent political support for FCEVs in passenger market, since this influences investments in vehicle production and infrastructure. In Japan especially, but also Germany, to stimulate FCEV production and purchases there is room for more regulatory pressure – for instance through zero-emission obligations for automakers and fleet operators like taxis and public agencies.

However, the systemic nature of identified barriers suggests that remedial measures cannot be achieved by policy intervention alone. Actions must also come from industry. The underutilised state of refuelling stations in Germany and Japan points to a need to couple refuelling station development with fleets of FCEVs (e.g. taxis and commercial vehicles). In all three markets, economies of scale are needed in station construction and fuel delivery. This could be achieved by expanding the geographical scope of markets, with Japan cooperating with Korea and China, California with other states, and Germany with neighbouring countries. Other strategies include sectoral coupling, by leveraging application opportunities for hydrogen and components across different transport sectors, including light-duty, heavy-duty, rail and shipping. All three markets also share an urgent need to increase the visibility of FCEVs in the public sphere. Taxis and ride-hailing fleets are attractive candidates. Automakers could supply reduced-price vehicles to such applications for their service as 'mobile billboards'. Likewise, if automakers are serious about penetrating the passenger market, more vehicle types are needed. In parallel, clearer signals to the market and politicians are required with respect to production plans, since opportunities for localised vehicle production also motivate supportive actions from policymakers.

In closing, several limitations could inspire future research. First, though we successfully identified the principal interaction pathways across different barriers, we could not assess the most influential. Potential ways to overcome this include quantitative surveys with stakeholders and cross-impact analysis (Godet, 2000). Also, since industry and government stakeholders are aware of barriers to FCEV deployment and constantly adapting strategies, monitoring iterative learning and subsequent outcomes would be valuable for other countries supporting hydrogen mobility. Finally, though the empirical evidence generated some insights into how the faster growth of BEVs especially is impacting FCEV diffusion, our theoretical and empirical approach did not focus on interactions between competing vehicle technologies. Future studies might benefit from explicitly addressing influences outside the FCEV market, using existing theoretical understanding (Phirouzabadi et al., 2020a, Phirouzabadi et al., 2020b, Geels, 2018) to inform analytical approaches.

Declaration of Competing Interest

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

Data availability

A collection of illustrative quotations from interviews that underpin the empirical analysis are compiled into supplementary data.

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Appendix A

See Table A1, Table A2, Table A3.

Table A1
List of interview respondents: Germany (n = 17).

Organisation	No. of respondents	Date
Government agencies		
EnergyAgency NRW	1	20/10/2020
Industry: Alliances		
H2 Mobility Deutschland	1	09/10/2020
German Hydrogen and Fuel Cell Association (DWV)	1	19/11/2020
Industry: Automakers		
Toyota Motor Europe (Belgium)	1	28/4/2020
Caetano Bus (Portugal)	1	26/11/2020
Honda R&D Europe Germany	1	30/11/2020
BMW Group	1	02/12/2020
Industry: Consulting		
HySolutions	1	14/10/2020
WSW mobility	1	19/10/2020
Ludwig Bölkow Systemtechnik (LBST)	1	30/10/2020
Hydrogen Power Storage & Solutions (HYPOS) East Germany	1	12/11/2020
Price Waterhouse Coopers (PwC) Germany	1	27/11/2020
EBISUblue	1	27/11/2020
Industry: Fuel suppliers		
Linde	1	30/9/2020
Shell New Energies	1	25/11/2020
Universities and research institutes		
Aachen University of Applied Sciences	1	01/10/2020
Fraunhofer Institute for Systems and Innovation Research ISI	1	30/10/2020
Total	17	

Table A2
List of interview respondents: Japan (n = 21).

Organisation	No. of respondents	Date
Government agencies		
Ministry of Economy, Trade and Industry (METI)	3	15/03/2019
New Energy Development Organisation (NEDO)	1	03/04/2019
Ministry of Economy, Trade and Industry (METI)	3	03/07/2019
Tokyo Metropolitan Government (Bureau of Environment)	2	07/08/2019
Tokyo Metropolitan Government (Bureau of Environment)	3	29/10/2021
City of Nagoya (Bureau of Environment)	2	05/11/2021
Industry: Automakers		
Toyota Central Laboratories	1	01/02/2019
Toyota	1	05/07/2019
Honda and Honda Central Laboratories	2	28/03/2019
Industry: Fuel suppliers		
Iwatani Central Laboratories	2	22/01/2019
Iwatani Tohoku Branch (Sendai)	1	02/07/2019
Japan H2 Mobility (JHyM)	1	07/03/2019
Japan H2 Mobility (JHyM)	1	06/10/2021
Industry: Associations		
Fuel Cell Conference of Japan	1	08/11/2021
Industry: Research institutes and consulting		
Japan Research Institute (Nihon Soken)	1	20/03/2019
Mizuho Research Institute	2	05/04/2019
Technova	1	29/10/2021
Universities		
Tama University	1	18/04/2019
Kyushu University (International Institute for Carbon Neutral Research)	1	10/02/2020
Musashino University	1	14/02/2020
Kyushu University (International Institute for Carbon Neutral Research)	1	8/11/2021
Total	32	

Table A3
List of interview respondents: California (n = 21).

Organisation	No. of respondents	Date
Government agencies		
California Air Resources Board (Sustainable Transportation and Communities Division)	1	07/03/2020
Port of Los Angeles	1	08/05/2020
California Air Resources Board (Mobile Source Control Division)	3	13/05/2020
California Energy Commission (Advanced Vehicle Infrastructure Office Fuels and Transportation Division)	1	19/05/2020
California Governor's Office of Business & Economic Development	1	05/06/2020
Industry: Automakers		
Honda (American Honda Motor Inc.)	2	28/04/2020
Hyundai-Kia (America Technical Center Inc.)	2	16/05/2020
Toyota (Toyota Motor North America)	1	27/05/2020
Industry: Fuel suppliers		
True Zero (First Element Fuel Brand)	1	28/04/2020
Air Liquide USA	1	15/05/2020
Shell New Energies	1	2/06/2020
Industry groups		
California Fuel Cell Partnership	1	29/04/2020
California Hydrogen Coalition	1	3/06/2020
Universities and research institutes		
University of California, Davis (Institute of Transportation Studies)	2	04/03/2020
University of California, Davis (Institute of Transportation Studies)	1	04/03/2020
International Council on Clean Transportation	1	04/03/2020
University of California, Berkley (Institute of Transportation Studies)	1	23/04/2020
Center for Transportation and the Environment	1	30/04/2020
University of Nevada Reno (Department of Geography)	1	19/10/2021
Arizona State University (School of Geographical Sciences and Urban Planning)	1	02/11/2021
Transit agencies		
AC Transit	2	28/04/2020
Total	27	

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trd.2022.103458.

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