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Drivers and Barriers to the Adoption of Fuel Cell Passenger Vehicles and Buses in Germany

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Abstract: As policymakers and automotive stakeholders around the world seek to accelerate the electrification of road transport with hydrogen, this study focuses on the experiences of Germany, a world leader in fuel cell technology. Specifically, it identifies and compares the drivers and barriers influencing the production and market penetration of privately-owned fuel cell electric passenger vehicles (FCEVs) and fuel cell electric buses (FCEBs) in public transit fleets. Using original data collected via a survey and 17 interviews, we elicited the opinions of experts to examine opportunities and obstacles in Germany from four perspectives: (i) the supply of vehicles (ii) refuelling infrastructure, (iii) demand for vehicles, and (iv) cross-cutting institutional issues. Findings indicate that despite multiple drivers, there are significant challenges hampering the growth of the hydrogen mobility market. Several are more pronounced in the passenger FCEV market. These include the supply and cost of production, the lack of German automakers producing FCEVs, the profitability and availability of refuelling stations, and low demand for vehicles. In light of these findings, we extract implications for international policymakers and future studies. This study provides a timely update on efforts to spur the deployment of hydrogen mobility in Germany and addresses the underrepresentation of studies examining both buses and passenger vehicles in tandem.

Keywords: fuel cell electric vehicles; hydrogen; battery electric vehicles; Germany; barriers; drivers; policy

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1. Introduction

After serving as the dominant technology for road transport for more than a century, the internal combustion engine is being replaced by electric drivetrains, and this transition is gathering speed [1,2]. Propelling this momentum are government policies and market trends seeking to reduce the contribution of road transport to climate change and to mitigate air pollution while modernising the driving experience with automation, electrification and digitalisation [3–5]. Two zero emission and electric drivetrains are wrestling for market attention, private investments and supportive government policies: battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) powered by hydrogen [6].

Relative to their fuel cell counterpart, BEVs are several years ahead on the technological learning and cost reduction curve, dominating yearly sales of zero emission vehicles (ZEVs). Indeed, the International Energy Agency reported that the global stock of BEVs reached around 4.8 million units in 2019 [7]. This dwarfs the on-road FCEV fleet in the same year (at 25,210 units) by more than two orders of magnitude [8]. While numerous actors in industry, government and research institutions have refuted the need for hydrogen to electrify the passenger vehicle market, stakeholders in several states and countries including Japan [9–11], China [12–14], Korea [15], California [16–18], Germany [19–21] and France [22] are actively supporting the deployment of both battery and hydrogen mobility. Underpinning these efforts is an appreciation of the distinct advantage of fuel cell powertrains relative to batteries. These include the ability to refuel a large vehicle population within a limited space, rapid refuelling times and better suitability for long driving ranges and for high utilisation vehicles [7,22,23]. Despite these strengths, the window of opportunity for hydrogen to play a significant role in the electrification of passenger vehicles is rapidly shrinking. This is largely due to rapid improvements in batteries in terms of power density, driving ranges, recharging times and production costs. In addition, the market penetration of BEVs is equally propelled by the larger availability of models, the eagerness of automakers to produce vehicles, and fewer cost hurdles when installing recharging infrastructure relative to hydrogen refuelling stations [7].

Yet the competitiveness of fuel cells shifts significantly when looking at heavy-duty applications such as buses and trucks. Relative to batteries, notable advantages of heavy-duty vehicles powered by hydrogen include longer driving distances, short refuelling times and fewer space, weight and cost trade-offs when storing propulsion energy on-board [23,24]. While expectations of the market prospects for hydrogen in the electrification of trucks are rapidly mounting [22], the history of fuel cell electric buses (FCEBs) is far more established. Demonstrations in public fleets reach back to the early 2000s in several locations around the world [25,26]. Meanwhile, multiple European, Asian and American cities continue to support the development and uptake of FCEBs in public transit fleets [14,19,27]. Here again, these efforts are propelled by a recognition of the clear advantages of FCEBs relative to battery alternatives. These include the ability to serve long-distance and geographically demanding routes (i.e., hilly or cold conditions), more on-board space availability and lower capital costs for refuelling infrastructure when serving larger fleets [22,28].

A case study on Germany provides an ideal opportunity to examine the varying factors driving or hampering the development and diffusion of both passenger FCEVs and transit FCEBs. First, Germany is a global leader in fuel cell development. Alongside nations like Japan, Korea and the United States, Germany boasts a long and continuing commitment to developing new technologies, generously funding R&D programmes and implementing strategies to commercialise mobile and stationary fuel cells. Public funding programmes and collaborations between industry, academia and government reach back to at least the 1970's [20,29]. Also, the national government, via several ministries and agencies, has actively assisted industry and research institutions to accelerate the technological development and deployment of fuel cells and hydrogen. This support was recently solidified and rendered more visible in Germany's *National Hydrogen Strategy*, unveiled in mid-2020 [30]. Second, another point of interest is that, although still nascent, the fuel cell mobility market is steadily emerging. Germany has the world's third largest fleet of FCEVs, with 1016 on-road passenger vehicles as of January 2021. Meanwhile, a total of 49 FCEBs are currently operating in public bus fleets in major cities such as Munster, Cologne, Wuppertal, Frankfurt, Hamburg and more [31,32]. Meanwhile, foundations for the rapid deployment of fuel cell mobility are firmly in place. As of December 2020, 90 hydrogen refuelling stations have opened [31]. Government and industry have committed to bringing at least 100 online by 2021, with further expansion (up to 400 stations) planned thereafter depending on the state of vehicle deployment [33]. Third, perhaps the most compelling reason to choose Germany as a case study lies in its status as an automotive superpower. It is home to globally renowned automakers such as BMW, Daimler (encompassing Mercedes Benz), Volkswagen (encompassing Audi) and Man. While all these companies have historically carried out R&D and demonstration activities for fuel cells, Daimler and BMW have been particularly active champions of hydrogen technology [34,35]. In the passenger vehicle space, Daimler has produced limited volumes of an SUV (*F-Cell*), while BMW is currently preparing a limited production run of its SUV (*X5*) for 2022 [36]. In the bus market, Daimler's *Citaro* and *Lion's City* by Man have also been produced in limited runs.

While the above description portrays a somewhat promising picture for the deployment potential of fuel cell transport in Germany, at present, batteries rather than hydrogen are dominating the electrification of passenger vehicles and buses. Indeed, according to data from the National Organisation for Hydrogen and Fuel Cell Technology (https://www.now-gmbh.de/en) current numbers for on-road vehicles (in January 2021) are 330,780 BEVs against 1016 FCEVs for passenger vehicles and 755 battery buses against

49 fuel cell buses. This situation thus provides a ripe occasion to deepen knowledge on the opportunities for a meaningful degree of penetration by hydrogen mobility in a globally significant market.

In this context, this paper identifies the principal drivers and barriers affecting the growth of the hydrogen mobility market in Germany for both privately-owned passenger vehicles (FCEVs) and buses (FCEBs) in public transit fleets. Using a structured analytical framework, we conduct our study from four perspectives: (i) the supply of vehicles (ii) refuelling infrastructure, (iii) demand for vehicles, and (iv) cross-cutting institutional issues. Using triangulated data sourced from expert surveys, interviews and document analysis, our structured comparison of the factors influencing the adoption of FCEVs and FCEBs allows us to objectively identify the most important drivers and barriers in each market as well as any differences.

The novelty and contribution of this study is at least three-fold. First, supported by a rich empirical dataset obtained from experts in industry, academia and government, this study provides a detailed and much needed update on the status of Germany's fuel cell mobility market. The challenges holding back the development of hydrogen mobility in Germany are well covered in early literature [20,21,29,34,35,37,38]. In recent years, however, scholarship on the continuing efforts by government and industry to overcome these obstacles has declined (a recent study by Coleman et al. on FCEBs [19] is a notable exception). Second, and from a methodological perspective, the systematic and holistic integration of quantitative and qualitative data from interviews, questionnaires and document analysis is the first of its kind in fuel cell mobility and hydrogen literature. Third, the up-to-date knowledge we provide on the conditions affecting the production and adoption of fuel cell passenger vehicles and buses provides a valuable resource for government and industry stakeholders working to accelerate the deployment of hydrogen mobility in other countries. These might include the United States, Japan, Korea, China and other European countries [22].

In the remainder of this paper, the following Section 2 presents the framework that guided our data collection and analysis. Methods are outlined in Section 3 before results are presented in Section 4. Finally, Section 5 summarises key findings and draws out implications for practice and scholarship.

2. Analytical Framework: Factors Influencing the Market Penetration of Fuel Cell Mobility

2.1. Overview of Framework

This section introduces an analytical framework developed to guide the collection and analysis of data obtained through expert surveys, interviews and documents. This synthesises a diverse body of literature discussing factors that positively or negatively influence the market penetration of fuel cell mobility. In addition to fuel cells (both mobile and stationary) and hydrogen, the influencing factors were sourced from studies on alternative transportation technologies such as battery, hybrid and automated vehicles. We also integrate factors emphasised in innovation literature like socio-technical transitions and technological innovation systems [39–41], since their relevance is widely recognised by hydrogen scholars [42–44].

The framework comprises a total of 20 influencing factors organised into four categories: (i) supply-side (i.e., the production of vehicles), (ii) infrastructure (i.e., refuelling stations and supply of hydrogen), (iii) demand-side (i.e., societal demand for vehicles), and (iv) institutional (i.e., cross-cutting measures falling across multiple categories). Building on previous research [9,16], working with these categories allows us to structurally integrate the four key dimensions of socio-technical change emphasised in technology policy literature [45] while achieving conceptual consistency with other studies on electric mobility governance [46–48].

2.2. *Description of Four Categories*

2.2.1. Supply-Side Factors

As shown in Table 1, the first category of influencing factors is focused on the cost, supply and state of fuel cell related technology and knowledge, environmental policies targeting automakers, and maintenance and repair networks.

If viewing these factors as drivers, market growth could be significantly accelerated if an abundant and diverse supply of vehicles and models was achieved by several automakers entering the market and committing to high production volumes [28]. This would then drive cost reductions in manufacturing through economies of scale [49]. Vehicle production costs will also be ameliorated by technological advancements that reduce the requirement for expensive materials such as platinum in fuel cell stacks and carbon fibre in fuel tanks [23]. When components and mass production methods become technologically mature, automakers can scale up production without fear of defects that might necessitate a vehicle recall and the significant financial losses incurred as a result. Environmental policies such as emissions limits (e.g., for CO_2 or air pollutants like NOx) and minimum production quotas for ZEVs are known to incentivise or force automakers to invest in clean vehicle development and production at a speed faster than market forces alone [3,50,51]. Meanwhile, support policies such as R&D subsidies and knowledge sharing networks also drive innovation and decrease economic and intellectual hurdles for automakers [24]. Finally, the establishment of sufficient repair or maintenance networks by automakers will reduce anxieties about the availability of after sales service, contributing to higher consumer confidence in the new technology.

However, these same factors can impede market growth. For example, when vehicle production volumes remain limited, a self-reinforcing loop occurs where per unit costs remain elevated and opportunities for economies of scale are lost [9,52]. This then reduces the market attractiveness of fuel cells relative to other propulsion technologies. In addition, if a wide range of vehicle choices encompassing sedans, SUVs, vans, buses etc. is not available, fuel cells will be unable to penetrate into diverse market segments [53]. Consequently, the low availability of vehicles then reduces the rationale for market investors and policymakers to commit to rolling out refuelling infrastructure [53,54]. Meanwhile, the supply of vehicles may also be impeded by technological difficulties in mass producing components like fuel cells and hydrogen tanks [55] or the lack of alternatives to expensive materials used in these [23,49,56]. The absence of strong environmental policies forcing investments in ZEV technologies will also likely hamper the growth of hydrogen mobility. When such policies lack, automakers tend to delay the introduction of ZEVs and favour conventional propulsion technologies due to sunk investments and expertise accumulated in production lines, chains of part suppliers and R&D programmes [57,58]. Finally, if faced with a limited availability of qualified repair personnel or networks, consumers may be unlikely to invest in hydrogen due to anxieties concerning the cost or inconvenience of servicing vehicles [28,59].

Table 1. Supply-side related drivers and barriers.

Influencing Factor	Explanation	Key Literature
1.1 Supply of vehicles	The volume of the current or expected production of fuel cell vehicles from various automakers and the availability of differing models and vehicle types.	[16,28,49,52,53,60,61]
1.2 Cost of production	The cost of producing fuel cell vehicles and associated components.	[9,23,24,49,50,52]
1.3 Technological state	The maturity, reliability and performance of core components in vehicles (e.g., fuel cell stacks and fuel tanks) and the ability to mass-produce these.	[9,23,28,49,55,56,62]

Table 1. *Cont.*

Influencing Factor	Explanation	Key Literature
1.4 Environmental regulations	The presence of policies such as vehicle emissions limits or minimum ZEV production quotas that target automakers.	[3,51,57,58,61]
1.5 Government support	The presence of government schemes to support technology production in the automotive industry such as R&D funding or information sharing networks.	[9,24,63]
1.6 Maintenance and repair networks	The availability of human resources and service networks from automakers to maintain and repair vehicles.	[28,59,64]

2.2.2. Infrastructure Factors

The second category of drivers and barriers shown in Table 2 includes two considerations. One is the availability, cost, profitability and technical reliability of refuelling stations. The other is the affordability and availability of low or zero-carbon hydrogen.

From the perspective of driving influences, market development is expected to accelerate when the rollout of refuelling stations occurs ahead of vehicles [54,65]. This sends positive signals to automakers that production volumes can be safely ramped up without stressing the capacity of refuelling infrastructure or inconveniencing drivers with limited opportunities to source hydrogen [16]. At the same time, low or declining costs for the construction and operation of refuelling stations, profitable business models (which largely depend on the volume of fuel demand from the on-road vehicle population) and financial support schemes from industry or government will motivate fuel suppliers to scale-up investments [9]. Also, by securing a cheap and steady supply of hydrogen, 'pump' prices will decline, reducing vehicle running costs. This would improve the market attractiveness of hydrogen mobility relative to alternative choices such as batteries or hydrocarbons [66]. Finally, the availability of cost-competitive and low or zero-carbon hydrogen will increase the value proposition of fuel cell transport in terms of climate benefits for consumers, investors and policymakers [61,64].

Table 2. Infrastructure related drivers and barriers.

Influencing Factor	Explanation	Key Literature
2.1 Availability of refuelling stations	The number and capacity of hydrogen refuelling stations relative to the population of on-road vehicles.	[16,18,53,54,65,67]
2.2 Cost of refuelling stations	The cost of constructing or operating refuelling stations.	[9,23,66]
2.3 Cost of hydrogen	The production and retail cost of hydrogen fuel for transport, as determined by production and delivery methods.	[24,66,68]
2.4 Profitability of refuelling stations	The ability to recover investments in refuelling stations for operators, as influenced by on-road vehicle numbers, government or industry support mechanisms, and construction or operation costs.	[24,64]
2.5 Economic support schemes	The availability of financial support schemes from government or industry to subsidise the cost of constructing or operating refuelling stations.	[53,61]
2.6 Reliability of refuelling stations	The reliability of hydrogen refuelling station equipment and the frequency of breakdowns and downtime.	[16]
2.7Availability of low or zero-carbon hydrogen	The availability of low or zero-carbon hydrogen fuel at an affordable price.	[16,61,64]

Conversely, these same factors can hamper market growth. For example, the deployment of refuelling infrastructure can be slowed by high construction or operation costs and limited opportunities for station developers to recuperate investments when vehicle populations are low [18,23,24]. The low availability of refuelling infrastructure can then decrease the market attractiveness of vehicles or even prevent their adoption if stations are not available nearby [18,67]. Equipment breakdowns at refuelling stations must also be avoided or minimised to avoid disruptions for drivers and the subsequent negative publicity this could evoke [16]. Similarly, if the retail cost of hydrogen is not competitive with alternative transportation energies, market attractiveness will suffer as a result of higher running costs for consumers [68]. For instance, many governments are anxious to increase the availability of renewable or low-carbon hydrogen for transport. Yet higher production costs relative to fossil fuel (i.e., 'grey') sources will challenge the business proposition of hydrogen for fleet or heavy-duty vehicles, where running costs are the core determinant of business feasibility [16]. Finally, market growth can be hampered by the negative perceptions of lifecycle carbon emissions if hydrogen is sourced principally from grey sources [61].

2.2.3. Demand-Side Factors

The third category of drivers and barriers listed in Table 3 pertain to demand-side issues such as the availability of purchase incentives, demand for vehicles from potential consumers, and awareness and familiarity in the public at large.

The presence of attractive incentives for consumers is known to propel the uptake of battery and hydrogen mobility [63,69]. While subsidies that reduce upfront purchase costs are heavily utilised [70], monetary incentives may also encompass reductions in vehicle registration charges and free or discounted charging or refuelling [16,50]. Non-monetary incentives are also important. Options include free or priority parking and exemptions from driving restrictions, such as car-free zones [4]. Additionally, high levels of societal demand for vehicles can also propel market growth by providing automakers and infrastructure providers with the confidence that investments in ZEV technologies will pay off. Demand will also increase when consumers perceive the look or performance of vehicles as desirable and when trusted or attractive brands generate enthusiasts or loyal followers [6,65]. Also, targeting market segments where vehicle demand is expected to propel market development. Optimal segments for fuel cells include fleet applications requiring long driving ranges and short refuelling times [22,54]. Finally, public awareness of the benefits of hydrogen mobility can accelerate market formation since positive attitudes tend to influence government policy and the purchase decisions of transit agencies (i.e., for buses).

From the perspective of market barriers, a lack of attractive incentives is expected to hamper the speed of vehicle uptake. This is because consumers are often unwilling to shoulder significantly higher upfront prices when purchasing vehicles for the sake of obtaining the lower running costs and environmental benefits of zero emission technologies [23,59,71]. Hesitancy to invest in more expensive battery and hydrogen vehicles is compounded by psychological factors such as anxieties related to poor access to charging/refuelling infrastructure as well as performance and reliability relative to internal combustion engines [6,18,72]. Also, when investing in propulsion technologies and choosing the focus of business models, automakers are heavily influenced by the preferences of users. Lastly, low levels of familiarity and public awareness of the environmental or economic benefits of fuel cell mobility are hampering market growth [6,53,63]. Public awareness tends to be negatively influenced by the limited visibility of hydrogen mobility owing to the lower production volumes of vehicles compared to battery counterparts [28]. This points to a need for outreach and education campaigns to raise public awareness and support [61,64].

Table 3. Demand-side related drivers and barriers.

Influencing Factor	Explanation	Key Literature
3.1 Consumer purchase incentives	The availability and attractiveness of monetary incentives (e.g., purchase subsidies, tax reductions) or non-monetary incentives (e.g., driving or parking privileges) to stimulate vehicle purchases.	[4,50,63,69,70]
3.2 Actual demand for vehicles	The degree to which market demand exists for fuel cell vehicles, with or without incentives.	[6,63–65]
3.3 Public awareness	The degree to which the general public is aware of hydrogen mobility and support its diffusion.	[6,53,63,73]

2.2.4. Institutional Factors

The final category of cross-cutting institutional factors affecting the above three categories appears in Table 4. Beginning with drivers, signals from politicians and government policy are crucial for market development [24,61,63]. If institutionalised through policies or formal statements, signals such as long-term commitments or targets from governments (e.g., for vehicle or station deployment numbers or funding amounts) tend to motivate private sector investments in fuel cell drivetrains when market uncertainty is high [9]. Establishing common standards and uniform protocols is also expected to propel diffusion [61,66]. This is especially important for buses and trucks where onboard storage methods and refuelling standards are still being shaped. Awareness of the need for standards is driven by experiences in the BEV market [74]. Competing configurations for charging interfaces and vehicle-to-infrastructure communication protocols has slowed market growth in many countries by creating uncertainty among technology manufacturers over which designs will prevail and which will become redundant [75]. Next, the formation of knowledge sharing networks is emphasised in innovation [39,41,76] and mobility literature [9,61]. Freely diffusing knowledge related to best practices in vehicle manufacturing, public policy and business models will accelerate learning by linking otherwise separated intellectual resources and stakeholders. Partnerships and coalitions are also important drivers since they too mobilise the knowledge, financial and technological resources of different actors [3,43,77]. Industry coalitions are also expected to increase the societal legitimacy of new technologies through political lobbying [40,78].

From the perspective of barriers, weak or inconsistent political support is argued to hamper the production ambitions of automakers. Weak signals may concern the availability of public funding for purchase incentives and refuelling infrastructure or the need for hydrogen in the mobility market [16,22]. In addition to a lack of common standards for hydrogen related technologies, institutional barriers may also arise from regulations. These may pertain to excessively strict safety standards for refuelling stations [9,22] or laws disadvantaging the economics of hydrogen production and refuelling stations compared to batteries or hydrocarbons [16]. Also, when knowledge sharing networks are weak or absent, innovation becomes stifled if best practices are confined to isolated pockets of stakeholders [43]. Meanwhile, a lack of dedicated lobbying activities from industry coalitions will hamper the growth of fuel cell mobility [16] if policymakers are more exposed to policy advocacy from competing technologies [39], such as batteries. Finally, the absence of industry partnerships that enable collaborative actions will shackle innovation if individual firms are forced to shoulder the investment risks from research projects, new business ventures and vehicle infrastructure [66].

Table 4. Institutional drivers and barriers.

Influencing Factor	Explanation	Key Literature
4.1 Political support and policy signals	The degree to which government actors support hydrogen and fuel cell technology through policies, statements and commitments.	[16,24,61,63]
4.2 Standards and regulations	The degree to which standards (e.g., for refuelling protocols and storage pressures) and regulations (e.g., hydrogen safety laws) influence the cost, risk of redundancy and diffusion speed for hydrogen mobility and infrastructure.	[24,61,66,74]
4.3 Knowledge sharing networks	The availability and effectiveness of measures to stimulate the sharing of knowledge and experiences for all relevant stakeholders.	[9,39,43,61]
4.4 Partnerships and coalitions	The availability and effectiveness of coalitions or partnerships that mobilise different stakeholders for joint actions like business development, research, political lobbying etc.	[3,16,39,40,77,79]

3. Methodology

3.1. Study Design

The basic approach of this study involves a systematic comparison of the factors influencing the market penetration of FCEVs and FCEBs in Germany. As explained below, data for this task was collected via three methods, each adhering to the structure of the abovementioned analytical framework:

(1) Expert survey: This elicited the opinion of experts versed in Germany's fuel cell mobility market about the principal factors driving or hampering the production and diffusion of passenger vehicles and buses. Drawing on scholarship both inside and outside the transportation field [63,80–83], this method helped to reduce the influence of the authors subjective judgement when identifying the most important drivers and barriers.

(2) Expert interviews: These were conducted with experts based in Germany and other European countries to obtain more detailed, qualitative information than that obtained through the expert survey.

(3) Document analysis: Secondary documents were consulted to build understanding into Germany's fuel cell mobility market and source evidence for specific issues identified in expert surveys or interviews.

3.2. Expert Surveys

Surveys were created by converting the 20 influencing factors included in the analytical framework into a series of explanations and questions. As shown in Table 5, respondents were firstly given a neutral explanation of each influencing factor before being asked: 'To what extent is this situation a driver or a barrier for efforts to grow the market for fuel cell passenger vehicles and buses in Germany?'. Respondents were prompted to assign a separate score for the FCEV and FCEB market using the following five-point Likert scale:

- Strong barrier
- Moderate barrier
- No influence
- Moderate driver
- Strong driver

Table 5. Focus of questions in the expert survey *.

Focus of Question
(i) Supply-side (production of vehicles)
1. The current or expected future supply of vehicles from German and foreign vehicle makers. 2. The cost of producing vehicles relative to other technologies (e.g., battery, hybrid, gasoline/diesel etc.) 3. The technological state (e.g., performance, reliability, maturity) of key components (e.g., fuel cells) and the mass production capability of German/European makers. 4. Environmental regulations from European, national or local authorities that target passenger vehicle or bus makers (e.g., for CO2 or NOX emissions, diesel engines and noise regulations etc.) 5. The current availability and effectiveness of government support (e.g., subsidies for R&D, knowledge sharing networks etc.) to accelerate technological innovation and improve production methods for vehicle makers. 6. The availability of repair and maintenance personnel or networks for vehicles and buses.
(Optional) In your view, what are the most important differences regarding the barriers or drivers related to the production or supply of fuel cell passenger vehicles and buses in Germany?
(ii) Infrastructure (refuelling stations and hydrogen supply)
7. The current availability of hydrogen refuelling stations. 8. The cost of building refuelling stations. 9. The production and retail cost of hydrogen fuel for transport. 10. The profitability of refuelling stations (which is influenced by business models, operation costs and vehicle usage levels). 11. The current availability and effectiveness of government policies or industry schemes (either financial or knowledge) that support the construction and operation of refuelling stations. 12. The technical reliability of refuelling stations and equipment. 13. The availability of low or zero carbon hydrogen fuel (at an affordable price).
(Optional) In your view, what are the most important differences regarding the barriers or drivers related to infrastructure (e.g., refuelling stations and supply/cost of hydrogen etc.) for fuel cell passenger vehicles and buses in Germany?
(iii) Demand-side (vehicle adoption)
14. The availability and effectiveness of government or industry schemes to incentivize the purchase of fuel cell passenger vehicles and buses (e.g., subsidies to reduce purchase costs). 15. The scale of demand for fuel cell transport compared to battery electric transport. 16. The scale of public awareness and support for fuel cell transport compared to battery electric transport.
(Optional) In your view, what are the most important differences regarding the barriers or drivers related to public awareness of demand for fuel cell passenger vehicles or buses in Germany?
(iv) Cross-cutting institutional issues
17. The degree of political support and policy signals from the EU or German government for fuel cell transport (e.g., political statements, diffusion targets, policy documents) 18. Standards and regulations that affect the production/usage of vehicles or the construction/operation of refuelling stations 19. The availability and effectiveness of measures to stimulate the sharing of knowledge and experiences for all relevant stakeholders 20. The availability and effectiveness of coalitions or partnerships that mobilise different stakeholders (e.g., vehicle manufactures, oil/gas companies, research institutes etc.) for joint actions like shared businesses, research or political lobbying etc.
(Optional) In your view, what are the most important differences regarding the barriers or drivers related to cross-cutting institutional factors for fuel cell passenger vehicles or buses in Germany?

* Note: After each of the above explanations, respondents were asked: 'To what extent is this situation a driver or a barrier for efforts to grow the market for fuel cell passenger vehicles and buses in Germany'?

Space was also provided at four locations to allow respondents to freely describe the drivers or barriers for each category they considered the most relevant for the market penetration of FCEV or FCEBs in Germany.

The survey targeted experts in industry (e.g., passenger vehicle or bus makers, fuel cell manufacturers, oil/gas suppliers, consulting firms etc.), research institutes and government agencies (including public-private organisations). Experts were identified via three means: (i) sourcing names and affiliations from publicly available documentation such as media articles and conference or workshop reports along with databases of projects receiving national or European government funding; (ii) sending email requests to the generic contact addresses of relevant organisations and requesting introductions to internal or external experts; and (iii) inviting respondents to nominate other experts at the end of the survey.

Surveys included an 'I don't know' option to avoid respondents feeling pressure to guess when lacking knowledge about a certain factor. Surveys were created with *Google Forms*. They were fine-tuned after testing during October 2020 with six international researchers possessing expertise in either fuel cell or electric mobility. The final survey was administered via email from 15 October to 31 December 2020. A common protocol was established. This involved contacting the targeted expert directly, explaining the research objective and requesting permission to send the survey. A *Google Forms* link was sent after permission was obtained.

Overall, 28 completed responses were received from 33 experts agreeing to participate. With a response rate of 85%, this volume of data was considered sufficient when compared to other studies using expert surveys [63,83,84]. The breakdown of respondent profiles appears in Table 6. While the knowledge of many experts is mainly concentrated on either FCEVs or FCEBs, we expected the majority to possess sufficient understanding of both markets to provide responses for most questions. Survey results support this expectation. That is, in a total of 1120 numerical data points collected (i.e., 40 responses from 28 respondents), there were only 79 cases (or 7% of the total) of 'I don't know' responses.

Table 6. Profile of experts (n = 28) completing survey.

Sector	Example Organisations	No. Responses	Portion of Total
Industry: Automotive makers (passenger vehicles and bus)	BMW Group, Honda R&D Europe (Germany), Toyota	4	14%
Industry: Alliances	German Hydrogen and Fuel Cell Association (DWV)	2	7%
Industry: Consulting firms	adelphi, Clean Energy Future Consulting Bystry, Element Energy, Ludwig-Boelkow-Systemtechnik, Roland Berger, Spilett New Technologies	9	32%
Industry: Equipment manufacturers (fuel cells and engineering)	Ballard Europe, Wenger Engineering	2	7%
Industry: Fuel suppliers	Linde Hydrogen FuelTech, Shell Hydrogen	2	7%
Research institutions	Centre for Hydrogen Bavaria (H2.B), Center for Solar Energy and Hydrogen Research (ZSW), The Hydrogen and Fuel Cell Center (ZBT)	7	25%
Government (including public-private)	EnergyAgency NRW, State Agency for New Mobility Solutions and Automotive (E-mobil BW)	2	7%

Notes: Organisations are listed in alphabetical order. Abbreviations are for common German names. Organisations not wishing to disclose their names are not listed.

3.3. Interviews

The interviews targeted experts in industry, research institutes and government or public-private organisations. As shown in Table 7, a total of 17 experts granted interviews between October and December 2020. We were unfortunately unable to interview relevant government institutions at the national level (e.g., Federal Ministry for Economic Affairs and Energy, National Organisation for Hydrogen and Fuel Cell Technology etc.) after repeated requests to multiple individuals were declined. The views of government stakeholders were thus elicited through interviews with other societal sectors.

Table 7. Details of interview respondents (n = 17).

Organisation (German Abbreviation)	Country (City)	Date
Government agencies (public-private)		
EnergyAgency NRW	Germany (Dusseldorf)	20 October 2020
Industry: Alliances		
H2 Mobility Deutschland	Germany (Berlin)	9 October 2020
German Hydrogen and Fuel Cell Association (DWV)	Germany (Berlin)	19 November 2020
Industry: Automotive (bus and passenger vehicles)		
Toyota Motor Europe	Belgium (Brussels)	28 April 2020
Caetano Bus	Portugal (Porto)	26 November 2020
Honda R&D Europe Germany	Germany (Offenbach)	30 November 2020
BMW Group	Germany (Munich)	2 December 2020
Industry: Consulting		
HySolutions	Germany (Hamburg)	14 October 2020
WSW mobil	Germany (Wuppertal)	19 October 2020
Ludwig Bölkow Systemtechnik (LBST)	Germany (Munich-Ottobrunn)	30 October 2020
Hydrogen Power Storage & Solutions (HYPOS) East Germany	Germany (Halle [Saale])	12 November 2020
Price Waterhouse Coopers (PwC) Germany	Germany (Berlin)	27 November 2020
EBISUblue	Germany (Kassel)	27 November 2020
Industry: Fuel suppliers		
Linde	Germany (Pullach)	30 September 2020
Shell New Energies	Germany (Hamburg)	25 November 2020
Research institutes		
Aachen University of Applied Sciences	Germany (Aachen)	1 October 2020
Fraunhofer Institute for Systems and Innovation Research ISI	Germany (Karlsruhe)	30 October 2020

The interviews were semi-structured and observed a basic protocol. This ensured each was: (i) conducted in English by the first author for a duration of between 60–90 min, (ii) recorded and transcribed in entirety, (iii) structured in accord with the analytical framework. To achieve the last point, we invited respondents to describe their views on how any of the 20 factors in the framework is influencing the development of the hydrogen mobility market. Given time limitations and varying expertise or interests, the influencing factors suggested for discussion were strategically chosen each time in accordance with the respondent's core area of activity. Room was also provided for respondents to freely provide information on other important factors or drivers influencing the production or adoption of FCEVs or FCEBs.

3.4. Document Analysis

A range of English documents encompassing academic studies and grey literature (e.g., reports and media articles) was collected from July to December 2020 with internet search engines and the Web of Science. We used varying combinations of keywords such as 'fuel cell', 'hydrogen', 'vehicles', 'buses', 'Germany' etc, in addition to specific topics arising during the research. With several documents published around 2012, this body of knowledge provided a basic overview of the development of Germany's fuel cell mobility market over the last decade.

3.5. Data Analysis

Qualitative data from the above three methods was collated and coded with the software MAXQDA. Codes were built from all 20 factors in the framework in addition to three sub-codes for FCEVs, FCEBs or both.

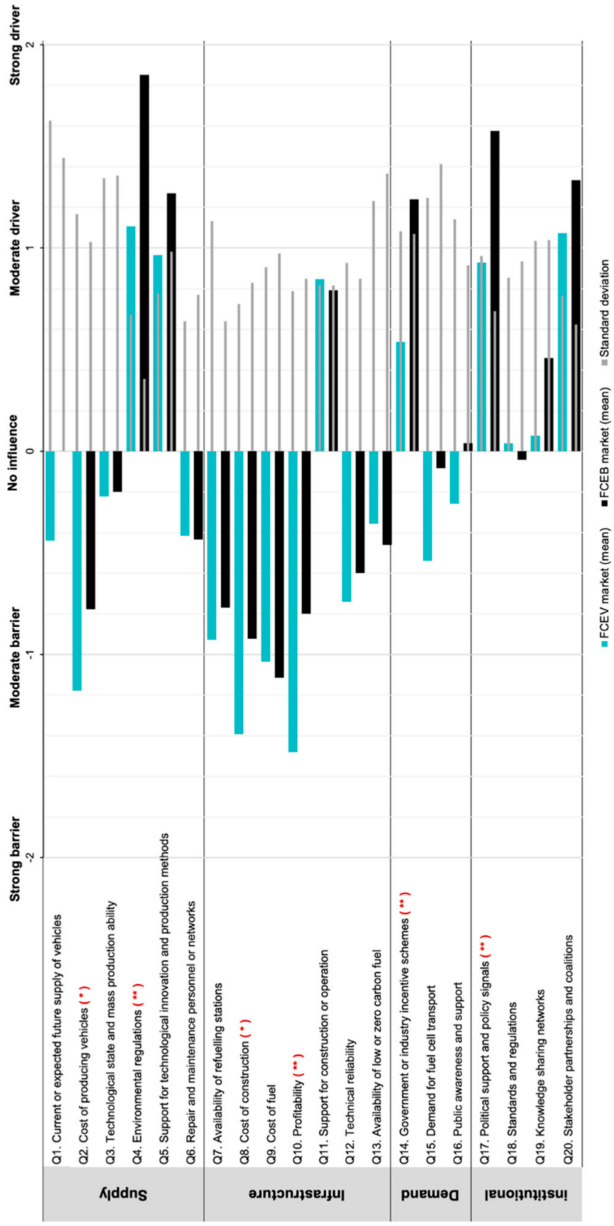

Figure 1. Summary of mean scores from expert survey ($n = 28$). Note: Asterisks in brackets indicate factors with a statistically significant difference in the mean score for FCEVs and FCEBs as calculated with a two-tailed Mann-Whitney U test (* = $p < 0.05$ and ** = $p < 0.01$).

Quantitative data from the expert surveys was converted to two outputs. The first, shown in Figure 1, displays the mean scores and standard deviation of responses for each question. The Likert scale responses were converted to scores ranging from −2 to +2. 'I don't know' responses were excluded from the analysis for that question only. We used a two-tailed Mann–Whitney U Test (with the alpha value set to <0.05) to detect factors with a statistically significant difference between the mean scores for the FCEV and FCEB market. The Mann–Whitney U Test was chosen over the t-test due to the unequal sample size for some questions after 'I don't know' responses were removed. The second output, shown in Figure 2, displays the full distribution of all responses obtained for each question.

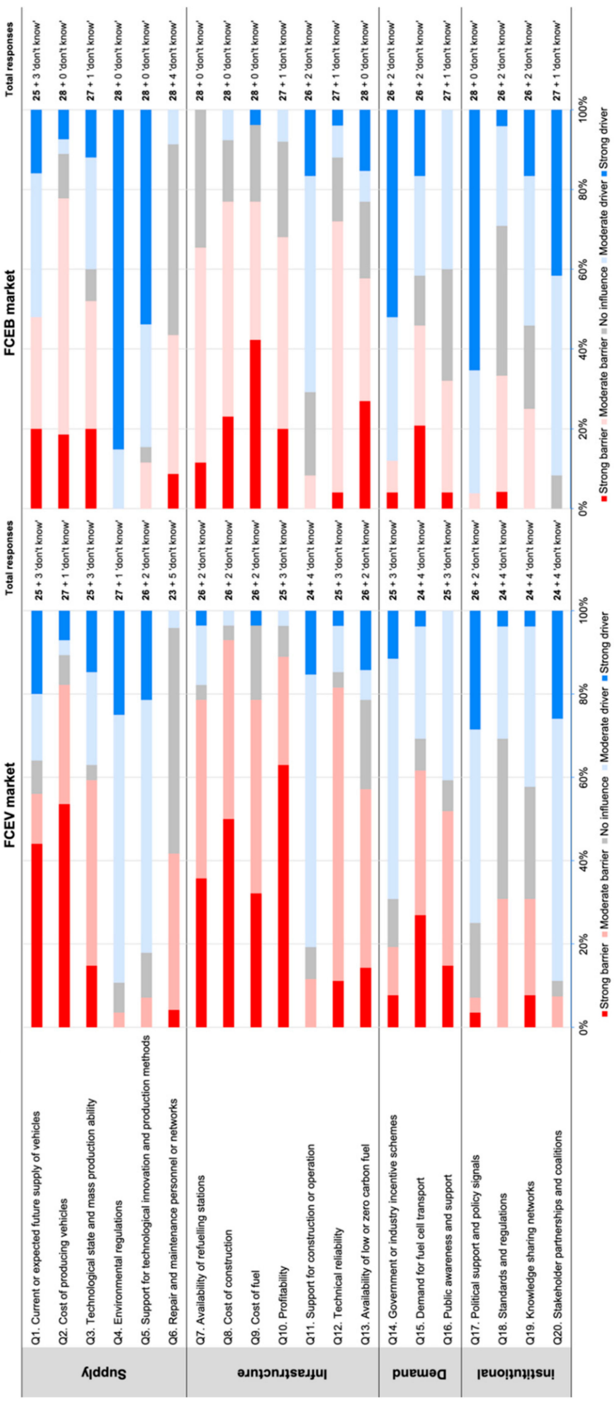

Figure 2. Full distribution of responses from expert survey (n = 28).

4. Results

4.1. Supply-Side Conditions

The survey results in Figures 1 and 2 indicate a strong recognition of two driving factors. The first is environmental regulations by European, national or local authorities (e.g., for CO2 or NOX emissions, diesel engines and noise levels etc.) that target passenger vehicle or bus makers (Q4). Environmental policy was reported as a decidedly stronger driver in the bus market than for passenger vehicles (statistically significant at p-value < 0.0001). The *Clean Vehicles Directive* from the European Union was cited in several survey responses (#11,24) and interviews (int. 4,9,12,16). Adopted in June 2019 and scheduled for implementation in April 2021, this regulation sets minimum clean vehicle purchase requirements for the fleets of public agencies, including transit buses. In the case of Germany, aggregated new bus procurements in public transit agencies must henceforth contain a minimum share of specified 'clean vehicles' (i.e., 45% for 2021–2025 and 65% for 2026–2030) of which half are zero-emission [85]. As one interviewed government actor (int. 9) explained, by sending a powerful signal that ' . . . there is no future for combustion engines', this regulation is forcing bus manufacturers to accelerate investments in ZEV drivetrains, with many developing both fuel cell and battery options. Local environmental regulations in Germany were also underscored in interviews, particularly in progressive cities like Hamburg (int. 1). Concretely, in the goal of phasing-out diesel engines to reduce NOX and CO2 emissions, regulations in Hamburg mandate zero-emission buses for all new procurements by public transit fleets after 2020. For passenger vehicles, scheduled to take effect in 2021, European Union CO2 emission limits [86] mandating a maximum fleet wide average of 130 grams of CO_2 per kilometre for new vehicles are also expected to spur the production of zero-emission drivetrains by German automakers. However, surveys (#11,24) and interviews (int. 8) asserted that their driving influence on the production of fuel cell passenger vehicles would be far weaker than regulations driving the bus market. Explanations included claims that Europe's CO_2 emission limits had been 'watered down by automotive lobbyists' (#24) and views that German passenger vehicle makers would meet the regulation principally with BEVs and plug-in hybrid powertrains.

The second driver highlighted in surveys concerns government schemes to foster technological innovation and production capabilities (Q5). The German government has historically nurtured collaborative technology development via competitive funding programmes for R&D and demonstration projects. For example, the inter-ministerial *National Innovation Programme for Hydrogen and Fuel Cell Technology* administered €1.4 billion over ten years, from 2007 to 2016 [33,87]. Extended for the period 2016–2026, this programme currently includes around €25 million in annual funding for mobility applications. Additionally, the German government has worked strategically to spur improvements in technical performance and mass production in the automotive fuel cell industry. The *Autostack Industrie* project implemented from 2017 to 2021 is a prominent example [33]. Building on successor projects at the European level, this mobilised automakers, part suppliers and research institutions with €30 million of German government funding to: (i) increase the power density of fuel cells and reduce platinum loading; (ii) establish common standards and manufacturing platforms; and (iii) raise fuel cell mass production capabilities. Positive evaluations of government support for technological development also surfaced across interviews. Although acknowledging that several technological challenges remain (e.g. how to increase mass production speeds without compromising precision and reliability), multiple respondents (int. 1,8,10,11,14) shared the view that the supply capabilities of German industry are now sufficient for mobility applications, and that government funding programmes have contributed to this. As one respondent (int. 14) explained: 'We have all the knowledge, and we have all the funds. We have *AutoStack Industrie*. We're all participating. We know that the stack which is being developed there can be manufactured at 30,000 units per year [. . .] But they [government agencies] cannot force industry to build those cars.'

Turning now to barriers, as the above statement suggests, other issues are hampering the ambitions of German automakers to produce vehicles. In particular, three were emphasised.

The first major obstacle concerns the cost of vehicle production (Q2). While this affects both passenger vehicle and buses, surveys reported this barrier as higher for FCEV production (statistically significant at p-value 0.035). Although actual production costs are not publicised, the retail price tags of both FCEVs and FCEBs are well above battery, hybrid and internal combustion vehicles. For example, 12-metre buses produced by European manufacturers for Germany cost roughly between €600,000 and €650,000 compared to around €400,000 for diesel counterparts (int. 9,16). Meanwhile, first-generation FCEVs from Toyota and Hyundai sold in Germany at around €78,500 and €65,500 over the past few years [88]. This is close to double the price of battery and hybrids. Interviews provided several explanations for these costs. For passenger vehicles, respondents (int. 2,5,8,11) emphasised how limited production volumes are currently preventing economies of scale and 'positive feedback loops' that drive rapid learning across industry. Also, automakers tend to balk at the costs of establishing high-speed, automated production lines and the logistical challenges of sourcing, producing and assembling parts, all of which threaten per-unit vehicle profitability (int. 10,11). In addition to fuel cell stacks, hydrogen fuel tanks are another bottleneck. This is principally due to the time and cost required to overcome engineering challenges and satisfy safety testing requirements (int. 4). For buses, although production costs were also cited as a barrier (int. 6,16), costs are decreasing rapidly and expected to continue falling (int. 9). For example, one European manufacturer could purportedly produce 12-metre buses at €450,000 each in a 1000-unit run (int. 9).

The second important barrier concerns the current or expected future supply of vehicles (Q1). Most experts judging this as a 'strong barrier' did so in relation to the FCEV market (see Figure 2). Numerous interviews supported this view (int. 1,4,5,6,9–14). At the time of writing, only two FCEVs are available for purchase in Germany—both from Asian automakers (i.e., Toyota from Japan and Hyundai from Korea). While both these automakers have committed to upscaling production, it is not certain that sales would be directed towards Germany where Asian brands lack a market share and delivery priorities are higher for home markets and California (int. 8). For German makers, Daimler once produced a limited volume of *F-Cells.* Yet production has since ceased, and ambitions to commercialise fuel cell powertrains have shifted towards trucks (and buses) through a joint venture with Volvo (int. 11) [89]. Meanwhile, the technological focus of other passenger vehicle makers once active in fuel cell development like Volkswagen has shifted to batteries. With no FCEV currently produced on home soil, this situation counters the historical expectations in industry and government that several domestic brands such as Daimler, Volkswagen, Audi and BMW would enter the market with significant production volumes [33,90]. Hopes for the emergence of locally produced FCEVs now hinge on the fruition of announcements by BMW for an SUV model in 2022 and rumours of the imminent production of a currently 'on the desk' model by Audi (int. 2,3,9). Regarding the hesitance of German automakers to enter the FCEV market, interviews (int. 2,11) underscored financial pressures on business models. These stresses have necessitated the selection of one zero-emission technology, breaking with historical trends to develop fuel cells and batteries in parallel. As one industry stakeholder (int. 2) explained: '(W)e have been discussing having two alternatives and burning money in R&D in both ways, knowing that, you know, one horse is faster than the other and that we probably put too much money on the second.' Beside R&D costs, the choice of batteries over fuel cells is influenced by numerous other factors including: (i) immense capital required to set up new production lines for either technology, (ii) time required to secure part supply chains for FCEVs, (iii) lower technological complexity in battery drivetrains, and (iv) fewer restrictions imposed by infrastructure availability for BEVs (int. 2,5,6,9,11). One automaker (int. 11) argued it would cost 'a billion euros' to enter into serial production for FCEVs. 'We have these two technologies, battery electric and fuel cell electric', they explained. 'And from our perspective, at the moment, the battery electric car is more advanced (...) So why spend another billion if we still haven't done our homework on electric cars'?

In the case of the bus market, however, multiple interviews (int. 7,8,12,16) and survey responses (Figure 2) positively evaluated the supply situation. This view reflects the willingness of several bus makers to invest in both fuel cells and batteries when building zero-emission portfolios. Supply is also driven by environmental regulations for bus fleets (discussed above) and demand for FCEBs from German and European cities based on an appreciation for longer driving ranges and suitability for tougher geographical conditions.

Yet the bus market is also grappling with supply challenges. Once again, although German makers like Mercedes Benz and Man previously produced limited runs of fuel cell buses, production activity has ceased. Again, this indicates a shift towards batteries (int. 16) within German and European manufacturers [32]. The immediate supply of buses now depends on the production volumes of European makers balancing fuel cell and battery portfolios such as Solares in Poland, Van Hool in Belgium and Caetano in Portugal. Due to this limited pool of suppliers, cities across Germany wishing to procure new FCEBs must frequently contend with long waiting times between orders and delivery, often between 12 to 18 months (int. 9) [32].

The third barrier emphasised in surveys concerns the availability of repair and maintenance personnel for vehicles (Q6). Although several interview respondents (int. 7,8,10) did not regard this as significant relative to other barriers, others (int. 6,13,16) along with documentation [90–92] stressed this issue regarding buses. This challenge encompasses two dimensions. One is that bus manufacturers are expected to ensure the availability of service networks and spare parts despite the limited volumes in circulation. This expectation stems from historical challenges for bus operating agencies to source new components and repairs for new vehicles (int. 7,17) [91]. The other challenge is that transit agencies and automakers share a need to retrain maintenance staff and upgrade depot workshops that have historically specialised in diesel engines (int. 16,17) [32].

4.2. Infrastructure

With the exception of government and industry support for the construction and operation of hydrogen refuelling stations (Q12), six of the seven factors examined in the infrastructure category were reported in the expert survey as considerable barriers for both the passenger vehicle and bus market.

The principal barrier emphasised for passenger vehicles concerns the profitability of hydrogen refuelling stations (Q10) (statistically significant difference at p-value 0.002). With some 90 stations currently operating and a further 16 under development [93], Germany's refuelling network (consisting mostly of retrofitted gasoline stations) will reach the goal of 100 stations during 2021. Although this refuelling network could in theory support a fleet of 40,000 vehicles (int. 4), in January 2021 there were only 1016 FCEVs in circulation [31]. Translating to a miniscule 11 vehicles per refuelling station, the ratio of vehicles to stations is insufficient to attain the annual sales target of 25 tonnes of hydrogen per station to 'build a business case' (int. 4). Although the current situation of underutilised infrastructure does not contradict the strategy of rolling out refuelling stations ahead of vehicles [33], industry consultants, fuel suppliers and automakers provided gloomy descriptions of prospects for profitability. These included: 'a nightmare' (int. 1), 'totally pointless' (int. 2), 'far from making a business case' (int. 12) and 'some stations are just standing there' and are little more than 'cash burning machines' (int. 4).

The business case for buses, however, is considerably more positive. Refuelling infrastructure investments in this market can anticipate a larger and steadier volume of fuel throughput due to the fixed refuelling patterns of transit fleets (int. 3,15). Also, if viewed on a per bus basis, the capital cost of installing hydrogen refuelling stations relative to battery chargers drops for large fleet introductions when factoring in electrical grid upgrade expenses. Learning from these experiences, station developers are now working to integrate refuelling dispensers for buses (and possibly trucks) into newer projects intended for passenger vehicles (int. 1,3,12).

The second barrier concerns the cost of building hydrogen refuelling stations (Q8). Again, this obstacle was reported as stronger in the passenger vehicle market (statistically significant difference at p-value 0.024). Concretely, a typical hydrogen refuelling station for passenger vehicles in Germany (containing two dispensers and a 24-h capacity of 500 kg) is reported to require approximately €1 million (int. 3,17) [94]. Although government subsidies cover half of this, the financial burden for station developers was nevertheless underscored in interviews (int. 15,17). Relative to buses, the higher construction costs in the passenger vehicle market were reported to occur due to: (i) the complexity of high-pressure 700 bar technology compared to 350 bar for buses, which necessitates expensive compressors and other equipment; (ii) the limited scale of the refuelling market, which reduces opportunities for economies of scale; and (iii) a lack of competition between station builders. This last issue stems from the guaranteed number of construction opportunities for the energy suppliers participating in the H2 Mobility partnership (established in 2014), currently charged with building and managing the national refuelling network. As one industry respondent (int. 15) explained: ' ... because they have almost guaranteed offtake for a number of stations, there's no real competition [...] You can buy the same station outside of Germany, for cheaper than you would have to pay within Germany'.

The third important barrier for the FCEV market pertains to the availability of refuelling stations (Q7). Although the mean score and number of 'strong barrier' responses for this factor is roughly comparable to the cost of hydrogen fuel (Q9), interview respondents were particularly vocal about the negative effect of limited station availability for passenger vehicles. Although Germany's national network will soon reach the impressive 100 station milestone (a number second only to Japan if viewed globally), multiple respondents considered even this degree of coverage a restricting factor. One survey respondent (#6) argued that the present network is 'sufficient for fuel cell vehicle enthusiasts, yet too scarce for regular people'. Interview respondents (int. 3,17) also drew attention to coverage gaps in the downtown areas of large metropoles like Munich (due to the concentration on periphery and autobahn locations) and weak interconnectivity between cities. The H2 Mobility alliance has a political mandate to develop up to 400 stations depending on vehicle demand. However, the snail-paced growth of passenger vehicle numbers is expected to dampen ambitions to expand the refuelling network beyond the initial commitment to 100 stations (int. 8). The attractiveness of Germany's refuelling network for FCEV drivers may thus remain limited in coming years. 'We have done our job' stated one respondent working on refuelling infrastructure (int. 4). 'Now somebody else [e.g., automakers] has to come around and show us that they are committed to hydrogen.' Additionally, some respondents (int. 3,4) stressed the need for further investments in building a European network to facilitate the cross-border travel behaviour of passenger vehicle users. One fuel supplier (int. 3) described the limitations of the present network as follows: 'You can travel around Germany. But the problem in Germany is that we are not an "island" like Japan or California [...] People living in Germany want to go to Italy, France, Austria, the Netherlands and Poland. But as of today, the network stops at the border'.

The only factor reported to be driving the market was the degree of support from government and industry for constructing or operating refuelling stations (Q12). In the passenger vehicle market, the H2 Mobility partnership distributes government subsidies to reduce the investment burden for developers during construction by up to 50%. For bus fleets in public transit agencies, a considerably higher degree of support is available. One actor (int. 9) reported that up to 90% of capital expenditures for refuelling station installation could be covered by assembling different government funding contributions from German and European agencies. Despite the positive evaluations of government support for construction costs, several respondents in surveys (#24,25) and interviews (int. 3) stressed the lack of assistance for operating expenses as a major hurdle. Although the public subsidies available through H2 Mobility reduce capital outlay requirements, the absence of financial support for operation places 'high pressure' on investors, reducing the likelihood of market-lead investments in refuelling infrastructure (int. 3 and surveys #10,25).

4.3. Demand-Side

Of three factors examined on the demand-side, the responses regarding the availability and attractiveness of government or industry incentives for purchasing FCEVs and FCEBs (Q14) indicate a judgement that, overall, the current situation is driving market growth. In the case of the remaining two factors, demand was reported as a stronger barrier for passenger vehicles (Q15).

The survey responses to Q14 appraised incentives for vehicle purchases as a considerably stronger driver for buses (statistically significant difference at p-value 0.004). Since 2021, up to 80% of the price difference between a fuel cell and conventional diesel bus is reimbursed to public bus operators purchasing vehicles from various ministries in Germany. Furthermore, in some cases operators can obtain the remaining 20% gap from local government agencies (int. 17). Government subsidies are particularly important drivers of vehicle demand since, without such support, public transit agencies could not afford the higher costs of fuel cell buses relative to batteries and diesel (12-m buses produced in Europe sell in Germany between €600,000 to €650,000 compared to around €400,000 for diesel counterparts). At the same time, however, adverse effects of public subsidies were reported. Concretely, two respondents working with fuel cell bus fleets (int. 9,16) contended that price ceilings of €650,000 and €625,000 in the ongoing European *JIVE* and *JIVE 2* programmes (launched in early 2017 and 2018 respectively [90]) have reduced the motivation for bus makers to cut production costs. While acknowledging the need for subsidies to lower financial barriers to FCEB procurement in public transit agencies, these respondents stressed the eventual need to reduce funding amounts. Under the current scheme, argued one respondent (int. 16), bus manufacturers 'see no necessity to reduce prices because, for the owner or the customer, it's the same price at the end. The rest is funding money. I think when we reduce funding money, the [retail] price [of FCEBs] will decrease in a fast way'.

Incidentally, the lower driving effect of incentives for FCEVs reported in survey results appears to reflect the lower availability of cash incentives for the passenger vehicle market. Corporate fleets purchasing more than three vehicles can receive up to 40% of the price difference between a fuel cell and conventional vehicle (raised to 80% in January 2021), while also reaping significant tax reductions due to the high purchase cost (int. 12,13). Yet financial incentives are much lower for individual buyers. Concretely, since 2016 the 'Environmental Bonus' scheme has provided subsidies (with contributions from both the federal government and automakers) to individual owners to reduce the retail price of ZEV and hybrid vehicles. In 2020, this scheme was reinforced to provide €7500 for ZEVs up to a purchase cost of €65,500 [95,96]. However, by granting higher subsidies of €9000 to vehicles priced under €40,000 in the goal of stimulating *affordable* rather than premium ZEV production, FCEVs are disadvantaged compared to batteries and plug-in hybrids by their higher sales price (int. 2). Moreover, the high cost of Toyota's first-generation *Mirai* (priced at €79,000 [88]) made it ineligible for this subsidy until release of the second model in 2021.

In the case of barriers, the most important issue relates to the lack of public demand for vehicles (Q15). Although not statistically different in the survey results, interviews conveyed this barrier as higher for the FCEV market. Concretely, the main issue concerns the lack of vehicle demand outside of corporate fleets. While publicly figures are not available, one industry consultant estimated the ownership profile of on-road FCEVs as 'around 80% for companies and only maybe 20% for private owners' (int. 16). Another consultant (int. 2) concurred by arguing: 'Honestly, I cannot remember seeing one private fuel cell car in Germany; and I have an eye for it'. Interestingly, despite the lack of FCEV purchases by individual owners, several interviews (int. 2,5,11,15) and survey respondents (#10,23,25) agreed that a non-negligible degree of appreciation and demand for FCEVs exists in the public sphere; largely by virtue of their suitability for long distances and high-load driving. Yet such positive views were countered by pessimistic accounts (int. 2,5,6,11,13,16). These respondents claimed that vehicle demand and public support for fuel cell mobility are vastly inferior to BEVs due to numerous, interlinked obstacles such as: (i) the high price of imported Asian FCEVs relative to competing options such as Tesla's, other BEVs and locally produced luxury vehicles; (ii) limited infrastructure availability; (iii) lower energy efficiency in hydrogen pathways relative to batteries; (iv) rapidly improving driving ranges and charging times of BEVs; (v) scepticism and criticism of fuel cell mobility in popular media, and importantly; (vi) the lack of models from *German* manufacturers. Regarding this last point, a respondent (int. 9) argued: 'Germans, in general, prefer to buy German brands. Toyota and Hyundai have a very low market share here in Germany with conventional passenger cars.' As another respondent (int. 13) explained, the lack of homegrown models has implications for public awareness, since the German media 'would be more likely to report on fuel cell vehicles if it was made from a German manufacturer'.

4.4. Cross-Cutting Institutional Issues

The most striking finding in the fourth category is the overall sentiment of experts that institutional issues are not significantly hampering the development of Germany's hydrogen mobility market. While the existence of two market barriers—namely, standards and regulations (Q18) and knowledge sharing networks (Q19)—was acknowledged, these were principally scored in survey responses as 'moderate' rather than 'strong' (Figure 2). Conversely, the mean scores for political support and policy signals (Q17) along with stakeholder partnerships and coalitions (Q20) indicate that, overall, these factors are positively influencing market development.

In the case of drivers and the specific issue of political support (Q17), survey results indicate an overwhelming consensus that policy signals from both German and European governments (as reflected in political statements, diffusion targets, policy documents etc.) are propelling the market. Interviews accounts concurred with this judgement. Some respondents emphasised the driving force of climate/energy policy and related technology and public spending budgets at the European level (int. 1,6,8). Relevant policies and technology forcing signals include the commitment to climate neutrality by 2050, the *European Green Deal* [97] hatched out in 2019 (which places heavy emphasis on green hydrogen in industry), and the *EU Hydrogen Strategy* unveiled in 2020 [98]. One industry consultant (int. 1) described this driving effect as follows:

' ... right now, hydrogen is a megatrend in Germany. But it's not maybe only in Germany, but in Europe [...] Within the last year, it was like the topic went not to the top, but through the top. And it was like, we have an extremely, extremely strong push from the politics side in every direction. And so, this is also a definitive force accelerated by the corona [virus] situation.'

Industry respondents also underscored the driving force of policies within Germany. The *National Hydrogen Strategy* [30] was frequently mentioned (int. 8,12). Launched in 2020, this is underpinned by a €9 billion budget, of which €2 billion is for mobility. Interestingly, one industry respondent (int. 2) drew attention to another indicator of national government support for hydrogen—the National Organization for Hydrogen and Fuel Cell Technology. Although the recent focus of this agency is purported to be on battery mobility, this respondent argued that this organisation's name itself indicates the historical enthusiasm in German politics for fuel cell mobility over batteries.

Despite these positive accounts, survey responses indicate a sentiment among experts that political support is considerably stronger for buses than for passenger vehicles (statistically significant difference at p-value 0.003). With this bias is somewhat discernible in the *National Hydrogen Strategy* [30], numerous interviews with automakers, fuel suppliers, consultants and academia (int. 4,6,9–12,16,19) echoed the sentiment that political support for fuel cell passenger vehicles has waned and shifted towards heavy-duty applications—and most notably *trucks*, where the comparative advantage of fuel cells is more evident. Some claimed that government policy has been influenced by the technology selection strategies and politically powerful, pro-battery discourse of automakers. Volkswagen, for example, has abandoned its fuel cell development activities and publicly denounced their low energy efficiency while promoting batteries [99,100]. Some respondents described 'disappointment' (int. 10) in industry and politics that German automakers are not currently producing passenger FCEVs. Such views, however, acknowledged the many financial pressures and technological barriers influencing the recent focus on batteries (see Section 4.1). Interviews also suggested a correlation between the degree of commitment to fuel cells in the automotive industry and support in political circles. As one automaker (int. 10) explained: 'political willingness drops more quickly if no European, especially if no *German* car manufacturer [emphasis added] is offering such vehicles on the market, because the German government has difficulty sometimes to argue why they spend so much funding money for car manufacturers not producing locally'. Another industry respondent (int. 11) concurred by stating: 'What governments always request from us is "When will you bring a car to the market? We don't want to ride in Japanese or Korean Asian cars with fuel cell technology. We want to have *German*-made cars" [emphasis added].'

Regarding stakeholder partnerships and coalitions (Q20), interview accounts (int. 1,8,13) supported the judgement of survey respondents that joint actions (e.g., business ventures, research, advocacy and lobbying etc.) by industry alliances and other stakeholder networks are driving rather than hampering the market. Indeed, industry alliances in Germany are both well-organised and plentiful and include H2 Mobility, the Clean Energy Partnership and the German Hydrogen and Fuel-Cell Association.

As for the effect of knowledge sharing activities amongst stakeholders (Q19), this was positively appraised in surveys and interviews. Yet several respondents (int. 9,14,16) working with FCEB fleets argued that efforts to share knowledge and experiences around vehicle and infrastructure operation, business models and so forth are more visible than in the FCEV market. This may be explained by the willingness of public transit agencies—presumably due to their status as publicly funded agencies—to actively share information with other stakeholders in Germany and Europe through workshops, conferences and publications etc. Conversely, in the passenger vehicle market, given that many adopters are private companies purchasing a limited number of vehicles, the motivation to learn from peers appears weaker.

In the case of barriers, the distribution of responses shown in Figure 2 reveals that many experts deem that market obstacles of an institutional nature do exist, even if only 'moderate'. Interviews support this observation, echoing the view that standardisation issues (Q18) are posing a significant challenge to the bus market. The first issue stressed by industry (int. 4,7,9,17) regards the emergence of so-called 'type IV' tanks in new buses and two problems prompted by this: (i) incompatibility with existing refuelling infrastructure, and (ii) increased economic burdens on refuelling station owners to upgrade equipment. In contrast to the superseded and steel-lined 'type III' variety contained in older buses, new type IV tanks are unable to cope with higher temperatures during refuelling and require pre-cooled hydrogen due to their plastic inner liner. With Germany's fleet of eight bus refuelling stations lacking pre-cooling equipment, one of two countermeasures is required, and possibly both (int. 9,14): (i) expensive upgrades to install pre-cooling equipment in existing and future locations wishing to service newer buses; (ii) a dispenser-to-vehicle communication protocol to avoid higher temperatures by adjusting refuelling speeds. A second standardisation issue concerns the pressure chosen for refuelling. While the bus market in Europe has adopted a standard of 350 bar and built infrastructure for this, multiple concerns were voiced (int. 2,3,5,14) that this might not be compatible with the future technological configuration of fuel cell trucks. For example, while Hyundai has chosen 350 bar pressure for its *XCIENT* truck, Japanese makers like Toyota and Hino are promoting higher pressure 700 bar to assure longer driving ranges and shorter refuelling times. Meanwhile, in developing its *GenH2* truck, Daimler has announced a commitment to liquid hydrogen, capable of even longer driving ranges. Germany and Europe are thus grappling with the difficult decision of choosing a uniform refuelling pressure and method (gaseous or liquified) for the truck market. This must balance the competing interests of refuelling station operators and automakers while, ideally, assuring some degree of compatibility with existing refuelling infrastructure.

5. Conclusions and Implications

This study systematically compared the principal drivers and barriers affecting the adoption of fuel cell passenger vehicles and buses in Germany. The overall picture painted by multiple lines of evidence is that Germany's hydrogen mobility market is struggling with multiple challenges and its pace of development is well below the positive expectations of stakeholders in past years. This is particularly the case for passenger vehicles.

Viewed through the four-category framework, the most significant barriers for passenger FCEVs reported in the expert survey and interviews concern the supply of vehicles, refuelling infrastructure and demand. Institutional issues were considered overall to be driving market development. On the supply-side, specific challenges relate to the cost of vehicle production, the limited availability of vehicles and the absence of contemporary German-made models. In the case of refuelling infrastructure, the nascent population of on-road vehicles is hampering prospects for profitability in refuelling stations and dampening the business case for building more when construction costs are still high. Furthermore, the soon to be completed network of 100 stations (and coverage in neighbouring countries) is probably insufficient to drive large mass-market demand. Meanwhile, demand challenges include the high purchase costs for vehicles and limited adoption of FCEVs in the public sphere beyond corporate fleets. Again, this latter factor appears influenced by the current lack of German-made vehicles.

The situation for buses is significantly more positive. This market is driven by powerful environmental regulations and political support. Most barriers are linked to infrastructure, particularly the cost of fuel and station construction. Yet these economic hurdles do not appear insurmountable due to the stronger business case for introducing hydrogen into public bus fleets than for passenger FCEVs. However, the bus market too is struggling with a limited supply of vehicles and high production/retail costs relative to competing battery options.

In identifying these challenges hampering the adoption of FCEVs and FCEBs, several hints of pre-conditions for future success emerge. One is that progress at reducing vehicle production costs and increasing the volume of supply (especially for *German*-made vehicles) needs to be accelerated. Another is that investments in refuelling infrastructure—both within and around Germany—and hydrogen production technologies remain essential. Only economies of scale, intensified investments and greater participation from Germany's automotive industry can achieve this. In the case of the FCEV market, the analysis highlighted a need to support the operating revenue of refuelling station operators and to further reduce the running costs of vehicles. Environmental policies targeting hydrocarbons are one solution. Although difficult to introduce politically, market-based approaches used in California to reward low-carbon transportation fuels and provide capacity payments to refuelling stations are one potential solution [16].

Given the scale of these challenges and greater success to date in the BEV market at increasing the supply of vehicles, reducing production costs and increasing driving ranges and charging speeds, one might question the wisdom of investing further in hydrogen. While it is highly probable that the scale of global investments in battery mobility will increase the lead of this technology over hydrogen mobility, the advantages of fuel cells are frequently overlooked. Beside the longer driving ranges and the comparable infrequency of refuelling, hydrogen refuelling stations can support a larger population of passenger vehicles than space-intensive battery recharging infrastructure [22]. They also provide mass-market electric mobility solutions when installing home or public charging infrastructure for BEVs is difficult due to land restrictions or few privately-owned homes. Meanwhile, the mass-production of passenger FCEVs can drive cost reductions in common components used in heavy-duty vehicles through economies of scale [16]. Finally, the technological complexity and greater volume of parts required for FCEVs are both a boon and a curse. On the one hand, these issues raise production costs relative to BEVs and necessitate lengthy timeframes to assemble networks of part suppliers. However, several respondents in this study underscored the compelling potential of fuel cells to preserve the economic livelihoods of upstream businesses and workers in the automotive industry. As the production of internal combustion engines wanes in coming years, the transition to a battery-centric automotive industry risks creating widespread economic stress and unemployment in supply chains due to the need for fewer parts. Thus, it is important that all vehicle producing nations carefully weigh the pros and cons of allowing their passenger vehicle and bus markets to shift entirely towards batteries.

As implications for future scholarship, although Germany's struggles in upscaling fuel cell mobility cannot be boiled down to a single factor, the influence of battery mobility is significant. This further begs the question: Are both hydrogen and batteries needed for the electrification of passenger vehicles and buses? Some scholars have explicitly considered this question [6] or tackled other examples of competing decarbonisation technologies such as nuclear verses renewables [101]. Yet, with most scholarship focused on single technologies or socio-technical systems, there is room for more consideration of competing decarbonisation technologies in the field of energy governance and sustainability transitions. Relevant questions might include: How does the development and diffusion of one green technology affect the other in terms of innovation systems, market dynamics and the emergence of new socio-technical systems? How do market players respond to the dilemma of competing technologies and why? And additionally: Should policymakers intervene in markets to influence technology selection, why, and moreover, how?

Finally, a major limitation of this study was the decision to focus on experts rather than vehicle end-users. To build a more comprehensive understanding of the various factors influencing hydrogen mobility in Germany, future scholarship could integrate the experiences of vehicle users with knowledge gained from experts, both for private passenger vehicles and buses. Also, in proposing our analytical framework, we acknowledge its non-exhaustive nature and that more factors could be included.

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