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The hydrogen field in 2035: A Delphi study forecasting dominant technology bundles

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ABSTRACT

Hydrogen might play an essential role in mitigating climate change. It can be applied across a set of both easy and hard-to-abate use-cases. But, most hydrogen-based technologies are not yet market-ready. To prevent wrong investment decisions, both corporates and policymakers need transparency on where the use of hydrogen is most likely and which technologies will be required. Due to their interdependence, all hydrogen-enabling technologies (e.g., fuel cells, electrolyzers, liquid hydrogen shipping) should be seen as a field of interrelated technologies rather than a disjunct set. Past studies viewed single hydrogen-based technologies as isolated or resorted to demand forecasting without detailing the required technologies. Thus, we ran an adapted Delphi-study to create foresight for entire technology fields and create future scenarios purely from Delphi-data. Additionally, we provide an up-to-date holistic scenario-driven view on the future development of the technology field of hydrogen in the year 2035, including its consequences. We ran two interconnected Delphi studies with 50 subject experts. Our results recommend a more targeted research and investment approach to bringing sustainable technologies for the right use-case to market.

1. Introduction

Global warming has accelerated, and its impacts have become more hazardous and visible in recent years. To prevent substantial and irreversible changes to our ecosystems, economies need to switch from a fossil-fuel-basis to systems run on renewable energies (IPCC, 2022). One pathway for defossilization is using hydrogen as an energy vector (Wang et al., 2021). Hydrogen can be applied across a broad set of applications: Nowadays, it is mainly used as a feedstock element, e.g., in fertilizer production and the oil and gas value chain. In the future, hydrogen and its derivatives could substitute fossil fuels for heating, transportation, industrial energy, or grid balancing (Breeze, 2017; Hosseini, 2022; Özdemir and Unland, 2015). As a result, scholars forecast a significant global demand scale-up, potentially resulting in a medium-term supply scarcity (Wappler et al., 2022). Until 2050, the annual growth rate is assumed to be highest in the intermediate years of 2030 to 2040, following an S-curve uptake, as hydrogen is prognosed to start venturing into new application fields (Hydrogen Council, 2021).

However, for most hydrogen-based technologies, we need to increase technology and commercial readiness levels (Gül et al., 2019; IEA, 2022). Many of these problems originate from a lack of scale, missing investments, incomplete standards, and infrastructures (Ren et al., 2020). Bringing hydrogen technologies to market readiness is costly and thus frequently requires subsidization. In a review of 19 national hydrogen strategies from the year 2019, 35 out of 50 government support programs for hydrogen applications were focused on passenger cars, refueling stations, and city buses (Gül et al., 2019). However, it is uncertain whether hydrogen will become prevalent in these and other applications because they might be better defossilized with non-hydrogen-based technologies, i.e., battery-electric (Liebreich, 2021). Considering that transforming the economy will consume up to USD 150bn by 2030 (The Economist, 2021), it is essential to promote effective investment decisions. Thus, policy, as well as corporate decision-makers, need more clarity and transparency where the use of hydrogen is most likely.

While several studies have aimed to create the needed transparency,

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they focus on single hydrogen technologies (CIFS, 2021; Lee et al., 2022; Thoennes and Busse, 2014), analyze hydrogen impacts independent of the underlying technologies (Chen and Hsu, 2019), are geographically narrowly focused (Li et al., 2021), or simulate overall global hydrogen demands while disregarding technological details (Hydrogen Council, 2020; IEA, 2021b; Wappler et al., 2022). Even though Moreno-Brieva et al. (2023) and Arsad et al. (2024) gave patent-based insights into the evolution of hydrogen technologies, guidance on the hydrogen technology mix needed to support the hydrogen transition, especially during the transition period from 2030 to 2040, is limited.

To complicate matters, hydrogen's potential to defossilize our economies depends not on the proliferation of a few single technologies but on the evolution of interrelated technologies as the "hydrogen technology field" (Markard and Hoffmann, 2016; Unruh, 2000). With symbiotic benefits, these interrelated technologies may facilitate the widespread use of hydrogen across different industries, e.g., via sector coupling or bundling demands (Abdin et al., 2020). These interrelated technologies include electrolyzers, fuel cells, liquid hydrogen shipping, synfuels, turbine technology for hydrogen, and many more. Taking together the needs (1) for transparency to guide today's investment decisions to be ready for the transition period in the 2030s and (2) to investigate interrelated technologies jointly as the hydrogen technology field leads to the research question of how the hydrogen technology field will develop until 2035?

To answer that question, we use an adapted version of the Delphi method and provide a scenario-driven view on the future development of the hydrogen technology field in various use-cases along the entire value chain. We focus on the technology mix that might constitute the hydrogen economy in 2035. We do this via two discrete yet interconnected Delphi studies (further called Delphi 1 and Delphi 2), one focused on technological dominance and hindrance reasons. At the same time, the other one addresses the related outcomes.

Our study contributes to research in at least two meaningful ways. First, we complement existing Delphi studies on hydrogen (e.g., CIFS, 2021; Lee et al., 2022) by shifting the focus from individual hydrogen technologies examined in isolation to hydrogen as an integrated technology field. Here, we follow theoretical advances in technology strategy (e.g., Kapoor and Klueter, 2021), technology diffusion (e.g., Anderson and Tushman, 1990), and especially technology interactions (Sandén and Hillman, 2011) that highlight to account for the interplay between distinct technologies. We show that such a field-level perspective can generate novel insights on the future diffusion of hydrogen, which cannot be given by conventional approaches focusing on individual technologies. Second, we demonstrate how staging two interconnected Delphi studies allows research to create foresight on the effects of technology interactions within and between technology fields and on technology diffusion more generally. By solely relying on Delphi survey data, this approach does not require a multi-method approach or mapping out an exhaustive list of underlying drivers. Our approach could help researchers and practitioners in areas other than hydrogen to leverage the potential of the Delphi method to zoom in on technology interactions within and between fields and to better understand the implications of such interactions for the diffusion of individual technologies and the broader technology field they are part of.

The article is structured as follows: Section 2 elaborates on the background of technology diffusion and technology fields as the interaction of multiple related technologies. Section 3 provides an overview of the study design, detailing our unique procedure for conducting Delphi studies for technology fields. Sections 4 and 5 present the two Delphi studies, each with its own methodology and results. Section 6 integrates the results from both phases into a scenario perspective and explains our scenario creation methodology. Finally, Section 7 concludes the article, discussing implications for companies, policymakers, and academic research.

2. Background

2.1. Technology diffusion

The diffusion of emerging technologies is fraught with uncertainty (Rosenberg, 1996). Such uncertainty stems from a lack of knowledge regarding (1) the development of the technology (technology uncertainty), (2) its most suitable market (application uncertainty), (3) its prospective users and their preferences (user uncertainty), (4) the broader (eco)system of complementary actors and technologies it is embedded in (ecosystem uncertainty), and (5) the business model used to capture its value (Kapoor and Klueter, 2021). Different types of uncertainty often coexist and interact subtly to complicate things further.

Theory promises to support scholars and practitioners in better understanding and anticipating technology diffusion trajectories in the face of uncertainty. Most prominently, Rogers' (1962) theory of diffusion depicts the process of diffusion as unfolding across different user groups following a characteristic S-curve pattern. Subsequent work has begun acknowledging some of the complexities inherent in this process, especially as they relate to mainstreaming a technology. Most notably, Moore (1991) highlighted the challenge of crossing the chasm that often exists between early adopters willing to take risks to be at the cutting edge of technology development and the early majority that seeks clear benefits and minimal disruption. Going a critical step further, work on scaling technologies and innovation (e.g., Haidar et al., 2022; Wigboldus et al., 2016) challenged the conception of diffusion and technology mainstreaming as a linear, unidirectional, and well-contained process leading to the desired outcomes. Instead, the scaling of a technology across application areas, user groups, or geographies is seen as iterative, involving participation, adaptation, and translation. Importantly, scaling processes can affect (and be affected by) factors within and beyond the broader socio-technical system they are a part of, triggering positive or negative spillover effects for a potentially diverse set of stakeholders (Wigboldus et al., 2016). Such complex dynamics risk being seen as threatening incumbent technological, economic, and social regimes, potentially leading to resistance with notable implications for diffusion trajectories (Haidar et al., 2024).

An additional complexity arises because emerging technologies often do not evolve and diffuse in isolation. Instead, they co-evolve in technology bundles that jointly shape the evolutionary trajectory of the broader technology field (Kapoor and Klueter, 2021). Perhaps most intuitively, different technologies in a specific application area, such as internal combustion, battery-electric, and hydrogen engines in passenger vehicles, may be in direct competition. According to Anderson and Tushman (1990), a technological discontinuity such as the development of hydrogen drivetrain triggers an era of ferment as part of which several technologies and its variants compete for dominance. Once a dominant design emerges, the focus shifts towards gradually improving the dominant design in an era of incremental change until the technological discontinuity triggers the next iteration of this cycle.

However, technologies can also interact in ways other than competition and substitution (Sandén and Hillman, 2011). They might enable or complement each other and could even converge and become one (Pistorius and Utterback, 1997). In that regard, discontinuous technological change could benefit from efforts that leverage technological complementarities to bridge new and established technologies as well as the systems in which they are embedded. For instance, hybrid or bridging technologies such as plug-in hybrid engines could prove critical for the diffusion of technological fields such as electric mobility with far-reaching implications for related technology fields (Geels, 2002). This potentially competitive, symbiotic, or parasitic relationship among technologies highlights the crucial importance of studying co-evolving technologies within a field in interaction rather than isolation (Sandén and Hillman, 2011).

2.2. Recent foresight on hydrogen technologies

Hydrogen already went through three previous hype cycles: the first in the 1970s induced by the global oil price shock, the second in the 1990s when climate concerns became salient, and the third in the 2000s when oil prices increased sharply and discussions on "peak oil" arose. In all cases, enthusiasm about hydrogen declined when the underlying "trends" became less prominent or oil prices normalized (Gül et al., 2019). To understand possible diffusion trajectories in light of such complexities, hydrogen has been a subject of technological foresight for decades (Stevenson, 2010; Valette et al., 1978). Foresight activity peaked during each of these hype cycles, as summarized by McDowall and Eames (2006). In more recent years, a comparison of uptake scenarios was compiled by Stevenson (2010) and Wappler et al. (2022). Table 1 is based on this work and briefly reviews prior Delphi studies on hydrogen technologies.

While clearly valuable, most of the existing Delphi studies focus on individual hydrogen technologies (CIFS, 2021; Lee et al., 2022; Thoennes and Busse, 2014), analyze hydrogen impacts independent from the underlying technologies (Chen and Hsu, 2019), focus on single geographies (Li et al., 2021), ignore hindrance reasons (Joergensen et al., 2004) or risk being outdated (Valette et al., 1978).

In retrospect, existing forecasts for the uptake of hydrogen usage in the global economy proved overly optimistic. A prominent example is the EU's forecast of a 5 % hydrogen share in passenger cars by 2020, which it failed to achieve (Demirbas, 2017). At the same time, other sustainable technologies such as batteries and solar even overshot their predicted learning rate, leading to a substantial cost decline and higher market uptake compared to fuel cell solutions (Hellstern et al., 2021). Similarly, the industry association "Hydrogen Council" attempted to forecast the year in which hydrogen-based technologies should become cost-competitive against the currently dominant technology and the best green alternative based on assumed learning rates on the total cost of ownership (Hydrogen Council, 2020). However, the recent uptake of electric heat pumps for private housing heating (ideally run with renewable electricity) might lead to more buildings being disconnected from the gas grid. Even a hypothetical future cost advantage would generate no technological dominance for hydrogen boilers. In this example, the faster time-to-market of heat pumps marks the infliction point, which leads to lock-in on direct electricity use due to the change in the underlying infrastructure, rendering previous assumptions on the diffusion of hydrogen technologies in this application area obsolete. Indeed, in many other use-cases, the discussion also comes down to hydrogen-based vs. direct-electricity-use technologies (Ball and Weeda, 2015; Marchenko and Solomin, 2015). Especially since hydrogen is at first a defossilization problem itself (replacement of 100 megatons "grey" hydrogen) and only second a defossilization lever for other sectors, the efficient use (e.g., cost-efficiency, max. defossilization effect) must be limited to the "right" applications (Marchionna, 2023).

2.3. Towards a field-level perspective on the diffusion of hydrogen technologies

We argue that a field-level perspective on technology diffusion is particularly relevant for hydrogen technologies. Most hydrogen technologies, such as electrolyzers, fuel cells, or liquid hydrogen shipping, are exposed to all five sources of uncertainty. As a case in point, in potential application areas such as mobility (application uncertainty), there is still a lack of knowledge regarding the future competitiveness of hydrogen relative to established and other emerging solutions (technological uncertainty), the preferences of prospective users (user uncertainty), the supply and distribution of green hydrogen (ecosystem uncertainty), as well as the commercial viability given the current cost structure (business model uncertainty), all of which interact in nontrivial ways. Likewise, mainstreaming hydrogen technologies is fraught with challenges regarding path dependencies in the energy sector, incomplete standards, missing infrastructure, and lacking incentives for early investment, leading to a striking shortage of green hydrogen and the capacity of the system to produce, store, transport, distribute and eventually use it (Ren et al., 2020).

Based on learnings from prior hydrogen foresight and recent theory on technology interactions (e.g., Sandén and Hillman, 2011), we argue that the meaningfulness and accuracy of hydrogen foresight could be improved substantially by accounting for possible interactions among distinct hydrogen and non-hydrogen technologies. Such technology interactions can come in different forms, including competing (e.g., fuel cells vs. battery-electric drive trains) and complementary interactions (e.g., fuel cells and liquified hydrogen storage). They will have significant implications for the respective diffusion trajectories. The case for field-level foresight that accounts for technology interactions is particularly compelling in the field of hydrogen technologies, which not only compete with other technologies for dominance but are also inherently interconnected along the hydrogen supply chain from (1) hydrogen production (e.g., electrolyzer types), (2) hydrogen storage (e.g., gaseous underground storage), (3) hydrogen transportation and distribution (e.g., pipelines or ammonia shipping) to (4) hydrogen use (e.g., fuel cells or hydrogen boilers).

As such, the future diffusion and success of hydrogen as a technology field will depend not on the proliferation of isolated hydrogen technologies but on the effective co-evolution of the entire technology field as a key component of an integrated hydrogen ecosystem. Hence, there is a clear need for the foresight to move beyond individual technologies to examine the hydrogen field as a co-evolving set of technologies interconnected along the entire hydrogen value chain and jointly compete with non-hydrogen alternatives. Similarly, the potential economic consequences from the evolution of the entire hydrogen technology field must be viewed unanimously – but to do so, we need foresight on the technologies and their potential future proliferation in the first place.

Table 1
Overview of hydrogen-associated Delphi studies in academic research (based on V. Stevenson, 2010).

Source	Year of publication	Forecast period	Location focus	Topic focus
Valette et al., 1978	1978	1985–2000	Global	Production and consumption breakdown
Joergensen et al., 2004	2004	2020–2030	Europe	Consumption and production use-cases
Tzeng et al., 2005	2005	No time focus	Taiwan	Consumption in mobility applications
Yüzügüllü and Deason, 2007	2007	No time focus	Unspecified	Discovering divergent options in hydrogen production
Bristow et al., 2008	2008	2050	UK	Passenger transport
Hart et al., 2009	2009	2019–2024	Global	Hindrance reasons for fuel cell uptake
Chang et al., 2011	2011	No time focus	n/a	Hydrogen production
Stevenson, 2012	2012	2020–2050	Global	Hydrogen contribution to global energy demand
Thoennes and Busse, 2014	2014	2030	Global	Performance parameters for automotive fuel cells
Chen and Hsu, 2019	2019	Varying per projection	Taiwan	Hydrogen ecosystem
Li et al., 2021	2021	Varying per projection	China	Hydrogen ecosystem
CIFS, 2021	2021	2040	Global	Hindrance reasons and drivers for fuel cell uptake
Lee et al., 2022	2022	n/a	South Korea	Hydrogen fuel cell power generation

3. Study design

3.1. Choice of technology foresight methodology

While different understandings of technology foresight exist (Porter, 2010), we aim for technological foresight to draw future scenarios and identify influence factors or trends (Gausemeier et al., 1998). Foresight creates a basis for decision-making across different stakeholder levels (e.g., individuals, businesses, industries, ecosystems, politics) (Powell, 1992). However, it can never be entirely precise; it merely tries to anticipate the most likely future outcomes in a range of scenarios (Saritas and Oner, 2004). To achieve these goals, techniques can be classified into three categories: exploratory, normative, and a combination of the two (Cho and Daim, 2013; Roberts, 1969; "Technology Futures Analysis,", 2004).

Exploratory techniques are projections of the future based on current trends extrapolated with assumed progress rates (e.g., S-curves, bibliometric analysis). In comparison, normative approaches asses the path necessary to reach a certain future outcome (e.g., multi-criteria analysis, backcasting). Lastly, exploratory/normative techniques such as the Delphi method, Scenario Planning, or Technology Roadmapping integrate elements to offer a nuanced approach. The Delphi method integrates expert opinions to reach a consensus on future trends (Beiderbeck et al., 2021a). Scenario Planning explores potential futures and how they might occur (Amer et al., 2013). Technology Roadmapping plots a strategic course from the current state to the desired future (Daim et al., 2014).

Delphi studies are well suited for technological forecasting, especially regarding emerging technologies. As such, foresight helps stakeholders make sense of - and deal with - the various sources of uncertainty regarding the development and diffusion trajectories of individual technologies or broader technology fields, thereby providing a basis for effective decision-making under uncertainty (Powell, 1992).

Delphi studies have become a standard tool in foresight research that have been used, for example, in engineering and technology settings (Flostrand et al., 2020). It is often the only method to run large-scale national or industry-wide forecasts with a broad set of stakeholders (Martino, 2003). Developed in the 1960s by the RAND project, Delphi studies are often described as structured, systematic, and interactive expert panel-based forecasting techniques. Initially, the primary focus was creating consensus about specific questions among experts (Dalkey and Helmer, 1963).

Today, Delphi studies are widely used to derive and discuss opinions from groups of experts (Landeta, 2006). Methodologically, Delphi studies rely on evaluating clearly defined projections, which experts evaluate in various survey rounds that are increasingly conducted in real-time via dedicated online platforms (known as RT or Real-Time Delphi) (Gordon and Pease, 2006; von der Gracht and Darkow, 2010). Real-Time Delphi studies promise to contain common issues of round-based formats, like high dropout rates, low interaction, low engagement, and long study duration with high moderator effort (Gnatzy et al., 2011). Importantly, for our purposes, the Delphi method is well suited for accounting for the complex interactions among technologies within and between technology fields, even though – to our knowledge – it has not yet been used for this purpose. Its expert-based format promises to capture decision-makers' sensemaking of multifaceted problems (Daim et al., 2013) and generate foresight in complex settings (Donohoe and Needham, 2009) with incomplete perspectives and ongoing debate (Fink-Hafner et al., 2019; Skulmoski et al., 2007). The Delphi method is versatile and can be methodologically adapted; it combines the strengths of qualitative and quantitative research (Donohoe and Needham, 2009) and can incorporate scenario approaches (Nowack et al., 2011).

Hydrogen must be seen as a technology field, for which foresight consequently should be created along the entire value chain and regarding technology dominance and potential economic consequences. In this complex, multifaceted setting our foresight study needs to accommodate perspectives on individual technologies and their interconnectedness in a scenario approach to open a field of potential futures. We use an adapted Delphi approach to efficiently create valid future scenarios for technology fields to achieve this.

3.2. Research approach

We used a fixed-horizon approach, looking at the year 2035, which is right in the middle of the predicted hydrogen transition. However, our horizon is shorter – only 13 years – than other studies (Alon et al., 2019; CIFS, 2021). This could lead experts to not fully detach from their current work, leading them to approximate current technological advancements linearly (Alon et al., 2019). We made this tradeoff to capture the transition period during which the hydrogen ecosystem is expected to scale. Additionally, a comparison to Table 1 shows that other hydrogen Delphi studies exist with similar time horizons.

To run a valid Delphi study, we started with desk research, 19 exploratory interviews, and a workshop to develop a framework addressing our research goal (Beiderbeck et al., 2021b). An important finding from our initial interviews was that experts tended to drift into technical nuances and started mixing the discussions about enablers of technological prevalence and possible consequences. Therefore, we concluded that to develop foresight for an entire technological field, our study design must differentiate between these. Consequently, we ran two Delphi studies in sequence but interconnected with the same set of experts. This dissected the questions on technological dominance (Delphi 1, see Section 4) from their consequences (Delphi 2, see Section 5). Fig. 1 shows this sequential procedure, which helped experts mentally separate dominance from consequences. We present the two Delphi studies in separate sections to allow the reader to better understand the methods and results associated with each study. Finally, we brought our results from the two interconnected Delphi studies together by creating two distinct scenarios (see Section 6) on how the future of hydrogen might evolve.

In both Delphi studies, we used a Real-Time Delphi, applying the procedure established by Roßmann et al. (2018) (see Fig. 2). Following methodological recommendations (Aengenheyster et al., 2017; Beiderbeck et al., 2021a) we ran the Delphi studies using the software Surveylet by Calibrum. This setup allowed experts to start, pause, continue, and even switch devices during their work on the survey. Experts could log on to the platform anytime to give their answers and reevaluate them based on other experts' opinions, which were aggregated and updated in real-time.

3.3. Expert panel

As in all Delphi studies, selecting the expert panel is key to ensuring the validity of results (Hasson et al., 2000). Following the literature, we selected diverse experts from various backgrounds, geographical regions, academic fields, and age groups (Beiderbeck et al., 2021a). We identified the experts through multiple sources: 1) From a cross-sectorial research cluster, 2) via online business networks, 3) acquired offline via a hydrogen industry convention, and 4) from the network of the researchers and pyramiding. All experts were invited individually after a background check by the researchers. There are different recommendations on the size of Delphi panels. Due to the breadth of our study, we settled down on a target of 40–60 experts, equivalent to other recent technology-focused Delphi studies (Jiang et al., 2017). We focused on acquiring a distributed group of experts from the different value chain categories to guarantee the validity of answers in each subsection of our survey. Finding experts who are fully confident in every use case is difficult; however, since the hydrogen industry is still nascent, the experts felt confident enough to reply to projections adjacent to or slightly outside their core expertise. We measured this by letting the experts state their domain and the level of confidence per step of the hydrogen value chain (production, transmission, etc.). Lastly, we asked them to skip any question they were not confident answering.

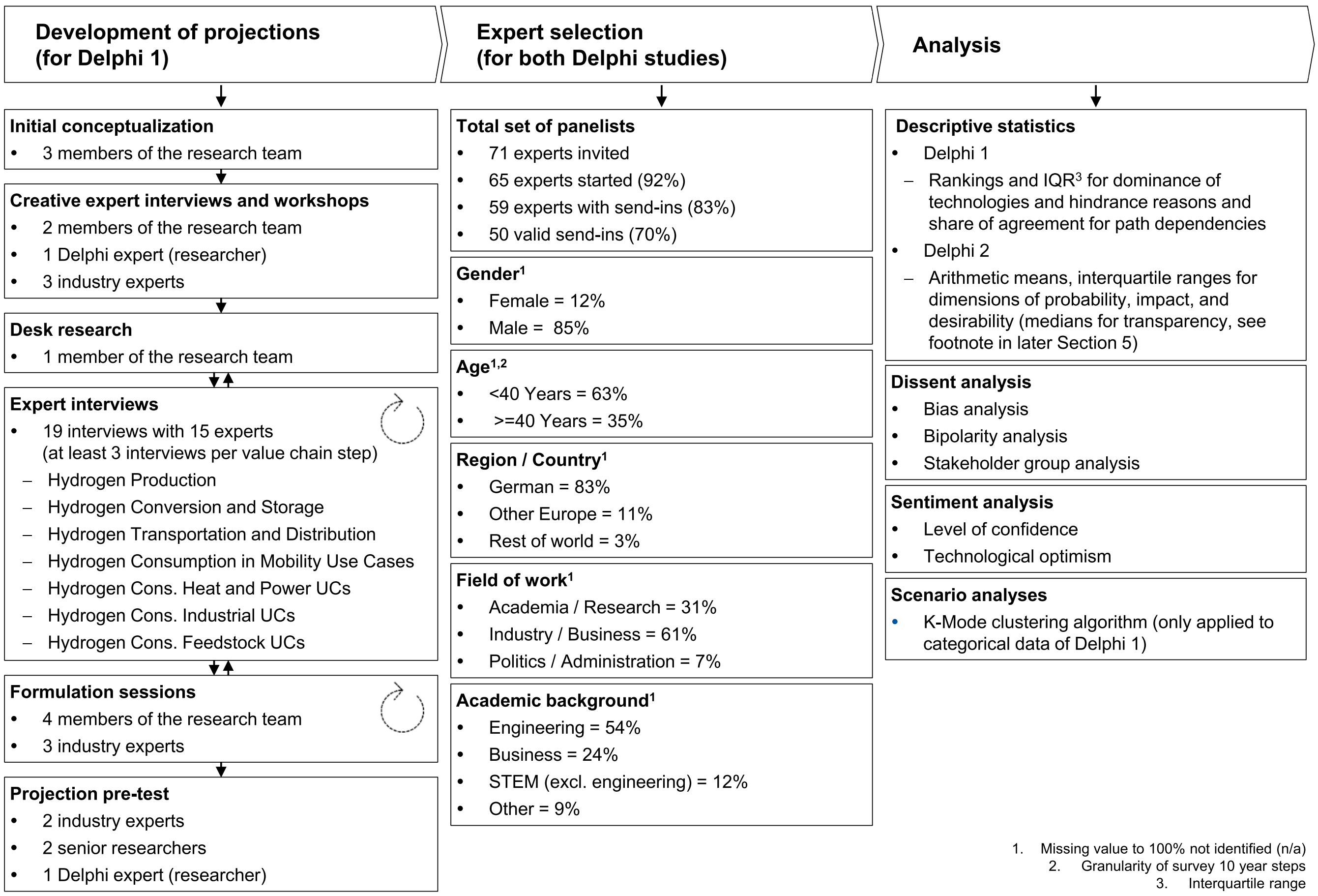

Fig. 1. Conceptual overview of the Delphi study approach.

	Technological Dominance (Delphi 1)	Technological Consequences and Pre-conditions (Delphi 2)	Scenario Development
Research question	Which technology for which use cases will become dominant and why?	What are the possible future technology consequences? Which impacts might occur?	What is the range of possible scenarios for the future of the hydrogen technology field? How do the scenarios differ?
Primary objective	Identification of dominant technologies for 19 use cases along the entire value chain	Assessment of the probability, desirability and impact of occurrence of the future projections	Definition of possible future scenarios and determination of key differences between them
Additional objectives	Analysis and evaluation of the hindrances for the implementation of technologies identified as dominant	Assessment of the dependencies of selected dominant hydrogen technologies (e.g., fuel cells)	Assessment how the experts who constitute the scenarios differ demographically
Section in manuscript	Section 4	Section 5	Section 6
Method of analysis	*see Section 4.1* • Ranking of technologies per use case + comments • Ranking of hindrance reason categories (political, economical, societal, technological) + comments • Selection of self-reinforcing effects (yes/no)	*see Section 5.1* • Rating of impact, probability and desirability on 5-point Likert scales • Rating of the influence on proliferation of a technology in one use case if it became dominant in another • For selected projections rankings of dominance	*see Section 6.1* • K-mode clustering of expert voting behavior in Delphi 1 to cluster experts with similar basic beliefs about technology proliferations • Definition of cluster count via silhouette method
Analysis	*see Section 4.2* • Qualitative and quantitative evaluation of dominant technologies, hindrance reasons and self-reinforcing effects • Usage of the results to select and enhance projections for Delphi 2	*see Section 5.2* • Qualitative and quantitative evaluation of future projections	*see Section 6.2* • Description and comparison of the two identified scenarios both quantitatively (along analysis of Delphi 1 and 2) and qualitatively (based on comments)

Fig. 2. Process for development of projections, expert selection, and analysis (based on Beiderbeck et al., 2021b; Roßmann et al., 2018).

During Delphi 1, 65 participants started the survey, 59 made send-ins, and 50 were valid (overview of panels' demographics in Fig. 2), of whom 36 also made valid send-ins in Delphi 2. In Delphi 1, the experts logged in and made adjustments on average 2.84 times, and spent 27 min per session. In Delphi 2, they logged in on average three times and spent 20 min. This sums up to ~100 h of combined efforts. We know that our participation rates are comparatively high, which we attribute to rigorously following up with experts upon their participation. We sent out weekly participation and reevaluation reminders.

4. Technological dominance (Delphi 1)

Delphi 1 focused on the emergence of hydrogen-based solutions in selected use-cases along the hydrogen value chain and compared them to alternative technological solutions. We asked participants to assess which technological solution would dominate a specific use-case in 2035, what hindrance reasons might exist, and whether the technology would benefit from any self-reinforcing mechanisms. Delphi 1 was run between May and June 2022.[1] Afterward, we conducted an intermediate analysis, which we shared with the experts two weeks later aiming to motivate experts to participate in Delphi 2 (Kawamoto et al., 2019).

4.1. Research methodology

4.1.1. Development of projections

For Delphi 1, we followed an analytically driven approach to select possible applications for hydrogen and alternative technical solutions. First, we aggregated 49 potential use-cases for hydrogen and the respective potential technical solutions from databases and reports of the International Energy Agency and reports issued by the Hydrogen Council (Hydrogen Council, 2020; IEA, 2021b, 2022). To further enhance the set of technologies, we ran extensive desk research and interviewed 15 industry and academic experts. In the next step, we clustered the use-cases in domains and categories along the hydrogen value chain (production, transmission, storage, usage). We then short-listed these use-cases to guarantee a comprehensive survey length that experts can answer in an acceptable period. For the selection, we followed a 4-step logic (see Appendix A), which we assessed with two selected industry experts. This resulted in selecting 19 use-cases (see Table 2). During Delphi 1, the participants ranked the technologies for the use-cases with a declining probability of becoming dominant (biggest share of new build/consumption/fleet, depending on use-case) by 2035. On average, we provided the experts with 7.5 technological solutions for each use-case to choose from. Before starting the Delphi, we cross-checked both the use-cases and the selected technological solutions with interviewees having the respective technological backgrounds. The discussion with experts about the relevance of the selected use-cases created value since the domain experts can gauge the relevance of a specific use-case in the mid- and long-term and pointed out existing interconnections of the use-cases.

> "For city buses, the discussion is over! It is a use case where battery electric drivetrains have already started to become prevalent." & "The method of long-distance transport also enables the type of applications the hydrogen is then used for; for instance, ammoniac transport would require a high level of purification for certain applications."[2]

Table 2
Overview of domains, categories, and use-cases.

Domain	Category	Use-cases/applications
Supply	Production	Hydrogen production
		Electrolysis Technology (decentral production at consumer)
		Electrolysis Technology (central production at renewable energy power plants)
	Conversion and Storage	Long term storage
	Transmission and Distribution	Long distance transport
		Regional distribution
Consumption	Consumption - Transportation	Commercial passenger vehicle (ride-hailing, car sharing, taxi)
		Heavy-duty truck
		Medium-haul commercial aviation (<250 PAX, <7000 km range)
		Ocean Container ship
		Private intercity passenger vehicle
		Short-haul commercial aviation (<160 PAX, <2000 km range)
		Construction vehicles
	Consumption - Building heat and power	Retrofit private home heat
		Retrofit residential housing/office heat
	Consumption - Industrial heat and power	Decentral industrial heat (high grade, e.g., metal or glass industry, >500 °C)
		Combined heat and power plants (CHP)
		Long-term energy storage (e.g., seasonal)
	Consumption - Industry feedstock	Primary steel production

4.1.2. Implementation

Before starting the survey, we provided each expert with the study's reason and method to ensure an understanding of the study. Additionally, the entire panel could contact the research team by phone or email to clarify terms and usability issues. We shared an individual pseudonymized access link to the platform with each expert. At first, experts answered demographical questions (gender, age, geography, main value chain categories, field of work, organization size, and academic background). To prevent data privacy concerns, we allowed experts to leave demographic questions partially or fully unanswered, which rarely happened. Before starting with the survey, experts chose which survey categories they would like to answer based on their expertise and specifically stated that individual use-cases could be skipped. Experts selected the most promising 3–5 technological solutions in each use-case and ranked them based on the likelihood of becoming dominant by 2035. We then asked for hindrance reasons and lastly required experts to state whether these technological solutions would have self-reinforcing effects leading to an acceleration once the "flywheel started spinning". We asked experts to provide comments on their reasoning.

4.1.3. Analysis

We ranked the technologies per use-case according to their assigned ranks and excluded technologies for which <10 % of experts voted to remove outliers. We then calculated the consensus for the top-ranked (median) technology via interquartile ranges (IQR), which is standard in Delphi literature (Beiderbeck et al., 2021a). When the IQR was smaller than 25 % of the selection range, we consider this a consensus (Beiderbeck et al., 2021a). We proceeded similarly with the hindrance reasons, which always had four manifestations (Political/Regulatory, Technological, Economical, and Societal). In the case of the question of the "existence of path dependencies", we provided the share of experts who agreed or objected. Lastly, we manually coded the written feedback to gain qualitative insights from selected comments. We followed an open (inductive) coding approach and created categories by cross-comparing the generated codes (see Appendix B for the abbreviated coding table). Finally, we prepared dissent and sentiment analyses, which focused on stakeholder group comparisons and the influence of

[1] Due to our study period, we controlled expert answers for the impact of the Ukraine/Russia conflict (also in Delphi 2). On average, experts believed the influence to be neutral (2.9 on a "1–5"-point Likert scale with a 0.85 standard deviation), which shows that this conflict did not influence the results of our study, further analysis of this factor was thus neglected.

[2] Quotes from pre-Delphi interviews.

experts' technological openness on the study results. The detailed methodological procedure for these can be found in Appendix C.1.

4.2. Results

Table 3 shows the results of Delphi 1. A consensus was reached on 13 of the 19 projections (ca. 70 %), indicating a high degree of agreement among experts. Depicting these results per technology domain, however, gives a more nuanced perspective: For use-cases in the domain "supply", only 2 out of 6 projections (33 %) reached consensus, whereas in the domain "consumption" 11 out of 13 projections (84 %) reached consensus. The results suggest that the perspective on where to use and not to use hydrogen-based technologies in consumption is much clearer than the view on which set of technologies will support the production, transportation, and distribution of the required hydrogen.

Hydrogen will presumably have the lowest importance in the transport sector. Looking into the dominance of hydrogen-based technologies in the domain of "consumption", experts agree that in 5 of 13 (38 %) cases hydrogen-based, in 5 of 13 (38 %) other green alternatives, and in 3 of 13 (23 %) fossil-based technologies will dominate in 2035. Diving deeper, only 1 of 7 (14 %) of transportation use-cases will be dominated by a hydrogen-based technology (fuel cell drive). At the same time, experts agree that in 4 of 6 (66 %) use-cases in heat/power/feedstock/industry applications will be hydrogen-powered in 2035. These results suggest that hydrogen will be central in developing non-transportation applications in 2035. Additionally, across the board, in 16 of 19 (84 %) cases, economic reasons are perceived as the main hindrance to hydrogen-based solutions becoming dominant. From the comments of the experts, we can identify two schemes: 1) experts believe that by 2035, the technology does not have sufficient market readiness to leverage scales for bringing down costs, and 2) experts think that (green) hydrogen has an efficiency disadvantage compared to direct (green) electricity usage due to the additional step of producing green hydrogen from green electricity. One expert commented: "*Superior efficiency will lead to direct electric use. It is rather a matter of economy than availability*".

Path dependencies play major constructive and obstructive roles in technological dominance (Klitkou et al., 2015). Generally, we look at technological (economies of scale and scope, network externalities, learning) and institutional (expectations and expectations of expectations, coordination effects, complementary effects) path dependencies (Sydow and Schreyögg, 2005). In our study, the perceived path dependency of the highest ranked technology can give hints on (1) where hydrogen-based technologies will prevail once a critical mass of "users/consumers" is reached due to lock-ins, i.e., from infrastructure build-ups, economies of scale, etc., and (2) where hydrogen-based solutions might remain insignificant due to lock-ins on other green alternatives even if hydrogen-based technologies might become cost-competitive. One example is passenger vehicles: Experts believe building up a second infrastructure next to charging stations for battery electric vehicles (BEV) is prohibitively expensive to build and run. Hence, the critical infliction point for "market readiness" was missed for fuel cell electric vehicles (FCEV). For instance, one expert let us know: "*BEV will be dominating everywhere [road-based transport]; it is cheaper, more mature, and in the mainstream strategy of OEMs [original equipment manufacturers]*". The path dependencies are perceived the highest on average (77 %) in the category of "consumption in transportation", where at the same time, most use-cases are perceived to be dominated by non-hydrogen-based solutions. The only exception is the case of heavy-duty trucks, where hydrogen is believed to be dominant and has a high

Table 3
Descriptive statistics for Delphi 1.

Use-cases/applications	N	Top Ranked Technology	Technology category	Selection range	Inter-quartile range	Dominant hindrance reason[1]	Path dependency[2]
Hydrogen production	46	Green Hydrogen	n/a	1–5	1*	Political/regulatory	81 %
Electrolysis (decentral)	39	PEM Electrolyzer	n/a	1–3	1	Economical	57 %
Electrolysis (central)	39	PEM Electrolyzer	n/a	1–3	1	Technological	55 %
Long distance transport	42	Ammonia shipping	n/a	1–5	2	Economical	82 %
Regional distribution	41	Admixing in existing natural gas networks	n/a	1–3	1	Economical	78 %
Long term storage	38	Gaseous underground storage	n/a	1–5	1*	Economical	64 %
Commercial passenger vehicle (ride-hailing, car sharing, taxi)	35	Battery electric vehicle	Green alternative to hydrogen	1–5	0*	Economical	76 %
Private intercity passenger vehicle	33	Battery electric vehicle	Green alternative to hydrogen	1–5	0*	Economical	72 %
Heavy-duty truck	33	Fuel cell electric vehicle	Hydrogen-based	1–5	1*	Economical	80 %
Short-haul commercial aviation	26	Kerosine turbine	Fossil	1–5	1*	Technological	77 %
Medium-haul commercial aviation	23	Kerosine turbine	Fossil	1–5	1*	Economical	79 %
Construction vehicles	27	Battery electric vehicle	Green alternative to hydrogen	1–5	1*	Economical	79 %
Ocean Container ship	21	Internal combustion engine (diesel/oil)	Fossil	1–5	1*	Economical	76 %
Retrofit private home heat	14	Electric heat pump	Green alternative to hydrogen	1–5	1*	Economical	89 %
Retrofit residential housing/office heat	14	Electric heat pump	Green alternative to hydrogen	1–5	1*	Economical	78 %
Decentral industrial heat (high grade)	14	Hydrogen burner	Hydrogen-based	1–5	2	Economical	67 %
Combined heat and power plants (CHP)	11	Hydrogen turbine	Hydrogen-based	1–5	2	Economical	71 %
Long-term energy storage	13	Power-to-gas-to-power	Hydrogen-based	1–5	1*	Economical	50 %
Primary steel production	10	DRI-EAF with hydrogen	Hydrogen-based	1–5	1*	Economical	50 %

(* indicates projections where consensus was reached, 1: for hydrogen-based technologies, 2: for technology ranked highest.)

path dependency, with 80 % of experts seeing dependency. For the domain of "(hydrogen) supply", we see strong path dependencies, especially in the transportation of hydrogen use-cases "long-distance transport" and "regional distribution", where infrastructure needs to be built up. Perceived path dependencies are, on average (49 %), the lowest in industrial heat and power and feedstock application. Here, already today, multiple co-existing technologies dominate the described use-cases.

We can mirror these results in the analysis of experts' comments. In total, we received 448 comments with an average length of 28 words, which we coded to reflect the pro and contra arguments for hydrogen technologies and experts' beliefs about the type of dominance technologies in the specific use-cases can achieve. We found that the strongest arguments for hydrogen usage were "the ability to reuse assets/tech/infrastructure", "flexibility", "social acceptance", "energy autarky", and "ability for sector coupling" (order in declining mentioning rate). The opposing factors were "existing or emerging lock-in on other (green) technologies", "missing regulatory support", "missing availability of products (cars, trucks, ships)", "low overall efficiency", and "the need to use rare hydrogen in use-cases where no other abatement technology is feasible". Interestingly, many of the pro arguments received can be placed on a socio-economic level, such as autarky, seasonal energy storage, or sector coupling. At the same time, opposing factors are often situated on the use-case or application level with reasons such as efficiency, market readiness, product availability, or costs.

Furthermore, all comments mention the dependence of green hydrogen on the availability of renewable electricity. Looking into the type of dominance, we found that 60 % of the comments suggested a single dominance of one technology in the specific use-cases due to lock-ins from infrastructure, investments, and economies of scale. However, this changes when depicting the results for domains only: In "supply", 63 % of comments indicated the co-existence of various technologies, while in transportation, 78 % suggested a sole technology to be dominant.

A detailed results section on dissent and sentiment analyses of Delphi 1 can be found in Appendix C.2. In short, these results show three important findings: (1) category experts are more skeptical regarding green technologies reaching dominance in the respective use case, (2) experts become more skeptical about the proliferation of green technologies when their confidence is higher, also outside of their core expertise area, and (3) even at a high technological openness, experts do not overestimate technological feasibility.

5. Technological consequences and pre-conditions (Delphi 2)

During Delphi 2, the expert panel evaluated projections focusing on preconditions for and outcomes from the projected technological dominances resulting from Delphi 1. Experts rated the expected probabilities of occurrence, the firm impact, and the subjective desirability. Additionally, experts answered follow-up questions on technological interdependencies between use-cases from Delphi 1. Delphi 2 was online between July and August 2022.

5.1. Research methodology

5.1.1. Development of projections

For Delphi 2, we followed other studies' approaches and recommendations to create the projections (Jiang et al., 2017; Landeta, 2006). We interviewed at least two experts per use-case category along the value chain (in total 15 experts) in a semi-structured format along the "PEST"-framework (political, economic, social, technological) (Beiderbeck et al., 2021a). Additionally, we conducted a workshop among the researchers, applied desk research, and leveraged the comments from Delphi 1 to create additional projections. In total, we identified 120 projections. To shortlist, we eliminated those projections directly connected to use-cases excluded during the shortlisting of Delphi 1. We further shortlisted in joint sessions with selected experts from the different categories of the value chain. We then selected those projections connected to topics and comments from the results of Delphi 1 by creating an interdependency matrix of projections and technologies (see Appendix D), leading to a set of 23 projections. Finally, we refined the formulation of the projections with experts and fellow researchers (Hasson and Keeney, 2011).

5.1.2. Implementation

During Delphi 2, we followed the same survey structure as in Delphi 1, with the sole difference being that we included a group of "general" questions that were not directly attributable to one of the value chain steps (see Table 4). Each expert was requested to answer the questions in this group (skipping individual questions possible) indifferently from his or her background and topic selection. In the questionnaire, we asked the experts to rate 19 (out of 23) projections on their expected probability, firm impact, and subjective desirability towards 2035. For "probability", experts could choose between 0 % and 100 % in intervals of 10 %. For the "impact" and "desirability" dimensions, we used 5-point Likert scales (see Table 4). The four other projections followed a different scheme. Three were projections where we asked experts to rank pre-defined answers. For the last one, which focused on evaluating cross-effects between technologies, we asked experts to rate the influence of technological developments in fuel cell technology for heavy-duty trucks on other mobility-related use-cases.

5.1.3. Analysis

We calculated consensus via interquartile ranges on the probability dimension. We calculated the averages and medians[3] of the respective expert groups for the probability, impact and desirability dimensions. Since the probability was answered via selecting from blocks of 10 %, we used the upper and lower range average to calculate the overall expert average. For the few ranking questions in Delphi 2, we used the same procedure as in Delphi 1. Again, we manually coded the written feedback. As in Delphi 1, we prepared dissent and sentiment analyses, which focused on stakeholder group comparisons and the influence of experts' technological openness. We also evaluated our results for a potential desirability bias (see Appendix F.1).

5.2. Results

Table 5 (for means, see Appendix E for medians) shows that 9 of 19 (47 %) projections where we analyzed the probability reached a consensus, indicating that many questions around technology consequences are still debated. Additionally, 8 of 19 (42 %) show a probability between 45 % and 55 %, showing that debate is still open, and the likelihood of occurrence is a mere chance. The questions around hydrogen consumption in transportation show the lowest average probability (38 %), whereas consumption in heat/power/industry/feedstock has the highest probability (54 %). On average, the dimension "impact" is considered to have a "moderate" or "major" impact, which shows that the set of projections is relevant.

In Delphi 1, fuel cell electric vehicles (FCEV) and heavy-duty trucks (HDT) were the only combination of a technology and a use-case where a hydrogen-based solution was perceived as becoming dominant by 2035. The projection on technological interdependencies of HDTs aimed to answer the question of where possible positive spill-over effects from

[3] Since our data for the probability, desirability, and impact dimension is on an ordinal scale, an analysis of the median values would be statistically correct, as one reviewer's valuable comment pointed out. However, since recent studies followed a similar approach in calculating means from the same type of data (Beiderbeck et al., 2021b), we use means in the main text to keep comparability. Additionally, we present the medians in Appendix E. In both cases the results are qualitatively similar.

Table 4
Overview of projections from Delphi 2.

Category	Abbreviation	Projection	Dim.
General	Energy cost trend	With the increasing renewable energy share and rising hydrogen production, the cost of energy (heating, electricity, transport, etc.) in my region will increase/decrease [Likert] until 2035 compared to today!	5-Point Likert
	Regional dominance	Which geographical region will dominate the supply of H_2-technology and equipment (e.g., fuel cells and electrolyzers) in 2035?	Rank
	Technology Openness	By 2035, in my region, the main regulatory support for defossilization will be technology-open, focusing on incentivization of CO_2e abatement rather than subsidizing a specific technology!	P, I, D
	Seasonality of energy cost	In my region, by 2035, the price for green hydrogen will vary significantly depending on the season (higher in the winter, lower during summer)!	P, I, D
	Electrical path dependency	Today's lack of hydrogen infrastructure in my region and missing technological readiness in many use-cases will lead to path dependency, preferring direct electricity use technologies until 2035.	P, I, D
	Startup innovation	Until 2035, the majority of technological and business model innovations in the hydrogen ecosystem will be driven primarily by new players (start-ups/scale-ups) in my home region's market.	P, I, D
	Market consolidation	The number of developers and manufacturers (companies) for fuel cells and electrolyzers will consolidate globally from now until 2035!	P, I, D
	Cross sectorial clusters	By 2035, hydrogen clusters/ecosystems which stretch over use-cases in multiple sectors of the value chain (cross-sectoral cooperation) will be more successful than single use-case-focused clusters.	P, I, D
	Impact on the labor market	By 2035 my home region/country will see a loss in local employment due to the renewable energy and hydrogen transition.	P, I, D
	Balancing business models	Until 2035, business models which monetize on optimizing the efficiency in balancing the supply and demand of hydrogen will grow relatively stronger than the average of the hydrogen ecosystem!	P, I, D
Production	Supply-side dominance	Which type of companies will dominate the production, transport, and distribution of hydrogen by 2035?	Rank
	The promoter of green hydrogen	Countries that have no "investment" in fossil energies today (extract oil/gas or provide infrastructure and machines) will lead the transition to H_2-economy and will thus dominate the supply of "green" hydrogen by 2035.	P, I, D
	Replacing OPEC	Until 2035, the world will see the formation of a hydrogen production organization (Oligopoly) similar to today's OPEC, focusing on the promotion of interests of hydrogen-producing and exporting countries (e.g., incl. caps on production volumes to prevent hydrogen price deterioration)!	P, I, D
	Global trading market	The hydrogen economy will produce a global public international trading network like today's oil trading market by 2035, incl. a "liquid" forward and spot market.	P, I, D
	Green H_2 certification	Until 2035, there will be a market for certification of the sustainable origin of hydrogen (green, free of forced labor, etc.)!	P, I, D
	Decentral or central H_2	Until 2035, most green hydrogen will be produced with grid power at consumption locations/on-premise (e.g., at steel mills, fertilizer plants, refueling hubs) and not centrally (at the location of electricity production, e.g., solar power plant), reducing the need for hydrogen distribution networks.	P, I, D
Transportation	Inefficient use penalty	There will be a "penalty tax"-controlled use of hydrogen (hydrogen is taxed higher where it is used inefficiently, i. e., in use-cases where there are other means of defossilization) favoring applications with no green alternative (aviation, feedstock, shipping, etc.) over others (e.g., road-based transportation, heating).	P, I, D
	Tech. inter-dependencies	If "Fuel Cell"-technology becomes dominant in heavy-duty trucks, this can also promote fuel cell dominance in …!	Likert
	Logistics H_2 infrastructure	Logistics companies and fleet operators of heavy-duty trucks will build and run their own hydrogen refueling infrastructure by 2035 to enable hydrogen transport before public infrastructure is sufficient.	P, I, D
Heat/power/ind./ feed	Diversification of H_2 producers	Hydrogen-producing countries will diversify vertically along the value chain beyond the mere production of hydrogen, i.e., into primary steel or base chemicals production, by 2035!	P, I, D
	Location shift of heavy industry	The hydrogen economy will lead to a major location shift of "high energy users" (e.g., steel plants, chemical industry) to locations with the cheapest hydrogen/renewable energy supply by 2035.	P, I, D
	Efficiency vs. technology	Until 2035, the main focus of greenhouse gas emission reduction in private housing will be answered through efficiency gains (heat isolation, denser living) rather than via new heating technology (hydrogen boilers, heat pumps, etc.).	P, I, D
	Symbiotic digitization	The need for reduced energy consumption in building heating systems will lead to a strong push in the digitization of energy (management) technology to increase efficiency.	P, I, D

(P, I, D = Probability, Impact, Desirability.)

applying FCEV in HDT might occur in other use-cases. Table 6 shows a high interdependence between HDTs and intercity, city buses, and medium-duty trucks. All other use-cases (passenger vehicles, ferries, river vessels, construction vehicles, and trains) are perceived as having minor chances to profit from the scaling of HDTs.

Analyzing the desirability, we found no evidence for a potential desirability bias and decided not to control our results. The bipolarity analysis shows that certain projections are highly debated among the experts; two are also perceived as highly impactful, making them highly relevant for future research. The results of Delphi 2 also confirm our findings from the sentiment analysis of Delphi 1 that experts are more skeptical in their areas of expertise. Detailed results on the dissent and sentiment analyses of Delphi 2 are available in Appendix F.2.

6. Scenario development

6.1. Research methodology

A Delphi-based scenario analysis aims to derive coherent future scenarios from gathered insights. A key task involves effectively aggregating the results of the Delphi survey to paint a cohesive picture of possible future scenarios. For this purpose, many Delphi studies cluster the average results across two or more dimensions (e.g., probability vs. impact vs. desirability) (e.g., Beiderbeck et al., 2021b). This clustering can be performed in various ways: manually based on visual analysis or by using clustering algorithms, often minimizing the average Euclidean distances between projections (Beiderbeck et al., 2021a). The choice of method and approach to aggregation depends on various factors, such as available data or the scope of the Delphi analysis. Clustering algorithms are particularly useful for more extensive Delphi studies, as they automate this process and make it more efficient. A crucial aspect in this context is the statistical treatment of the Delphi results before clustering. This step is critical as it significantly influences the quality and reliability of the resulting scenarios (Di Zio et al., 2021; Marozzi et al., 2022). In particular, Di Zio et al. (2021) highlight the importance of adequately considering the data scale (nominal, ordinal, or interval) and applying the appropriate clustering algorithm depending on the scale.

In this study, expert evaluations in Delphi 1 (Technology Dominance) form the basis for clustering. Unlike other Delphi studies, experts were not asked about probability or impact due to the questionnaire's

Table 5
Descriptive statistics for Delphi 2.

Abbreviation	N	Probability means	IQR[1]	Impact means	IQR[2]	Desirability means	IQR[2]	Dominant selection	Evaluation dimension
Energy cost trend	29	2.3[3] Sligh incr.	2[2]						5-Point Likert
Regional dominance	27		2[2]					Europe	Ranking of answers
Technology Openness	29	48 %	30 %p	3.9	0*	3.8	1*		P, I, D
Seasonality of energy cost	30	44 %	22.5%p	3.1	2	2.4	1*		P, I, D
Electrical path dependency	30	60 %	20%p*	3.6	1*	2.8	1.5*		P, I, D
Startup innovation	30	39 %	30 %p	3.4	1*	3.3	1*		P, I, D
Market consolidation	27	56 %	15%p*	3.6	1*	3	2		P, I, D
Cross sectorial clusters	29	66 %	15%p*	3.5	1*	3.8	1*		P, I, D
Impact on the labor market	28	25 %	20%p*	3.6	1*	1.8	1*		P, I, D
Balancing business mod.	28	55 %	10 %p*	3.2	1*	3.3	1*		P, I, D
Supply-side dominance	23		10 %p[4]					Today's O&G majors	Ranking of answers
The promoter of green hydrogen	26	47 %	30 %p	3.4	1*	3.2	1*		P, I, D
Replacing OPEC	25	46 %	35 %p	3.9	2	2.4	1.5*		P, I, D
Global trading market	25	54 %	22.5%p	3.4	1*	3.4	1*		P, I, D
Green H_2 certification	26	72 %	10 %p*	3.6	1*	4.1	1*		P, I, D
Decentral or central H_2	25	38 %	20%p*	3.4	1*	3	2*		P, I, D
Inefficient use penalty	24	26 %	20%p*	3.3	2*	2.9	2*		P, I, D
Technological interdependencies	25								Influence on other Use Cases
Logistics H_2 infrastructure	23	49 %	27.5%p	3.7	1*	3	1*		P, I, D
Diversification of H_2 producers	17	58 %	30 %p	3.2	0*	3.5	1*		P, I, D
Location shift of heavy industry	19	48 %	30 %p	3.9	0*	2.7	1*		P, I, D
Efficiency vs. technology	20	46 %	27.5%p	3.3	1*	3	1.3*		P, I, D
Symbiotic digitization	20	62 %	10 %p*	3.3	1*	4	2*		P, I, D

(* indicates projections where consensus was reached, 1: Consensus for IQR ≤8*0.25, 2: Consensus for IQR ≤5*0.25, 3: here the dimension is not "probability" but a 5-Likert from 1 = significantly increase to 5 = significantly decrease, 4: Consensus for IQR ≤3*0.25, P, I, D = Probability, Impact, Desirability.)

scope. Instead, experts ranked for each specific use-case (e.g., passenger vehicles) which technological solution (e.g., fuel cell, battery electric, internal combustion engine) would dominate. To identify similar decision patterns across the results of the 50 experts ranking up to 5 technologies (out of 10) for 19 different use-cases, we first decided to look only at the highest ranked (dominant) technology per expert. Second, we created an "expert-use-case-technology matrix". For this purpose, we coded each technology with a unique categorical identifier within each use-case. Then, we created a matrix containing this identifier for the highest-ranked technology per expert per use case across all use-cases. This matrix can be seen as a mathematical representation of each expert's individual voting behavior.

Subsequently, we split the matrix along the (sub-)domains supply, transportation, and heat/power/industry/feedstock. We used the silhouette (from R-package "NbClust") method to identify the optimal number of clusters (Sagala and Gunawan, 2022). Since the data was categorical,[4] we used the k-mode algorithm (Chaturvedi et al., 2001; Di Zio et al., 2021; Marozzi et al., 2022) to cluster the experts in groups. To test the approach, we visually compared the cluster results to the cluster expert's individual behavior. In the last step, we described consistent scenarios based on the results of the two studies for these clusters.

This approach identified two clusters of experts in each domain (hydrogen production, transportation, etc.) of the Delphi study (based on the silhouette graph in Appendix G). When an expert always fell into Cluster 1, we attributed the expert to Cluster 1 of the summary cluster. We did the same for Cluster 2. Those experts who did not answer any section in full[5] or who fell for some sections in Cluster 1 and others in Cluster 2 were omitted from the data for the scenario analysis. Ultimately, 20 were grouped in Cluster 1 (basis of Scenario 1), 9 in Cluster 2 (basis of Scenario 2), and 21 were omitted from the scenario analysis.

Table 6
Descriptive statistics for technological interdependencies of Delphi 2.

Technology	Mean	IQR
Intercity (coach) bus	4.6	1*
Medium duty truck	4.1	1*
City bus	4.0	1*
Regional ferry	4.0	2
Coastal and river vessels	3.8	2
Construction vehicles	3.7	1.5
Passenger train (regional)	3.5	1*
Freight train	3.3	1*
Commercial passenger vehicle (ride-hailing, car sharing, taxi)	3.2	2
Private intercity passenger vehicle	2.8	2

(* indicates projections where consensus was reached, dimension from 1 = not probable to 5 = probable, consensus for IQR ≤ 5 * 0.25.)

6.2. Scenarios for the future of hydrogen

The highest divergence between the clusters exists in the domain "supply", where the two groups ranked different technologies on top in 5 out of 6 topics, followed by "Heat/Power/Ind./Feed" with 4 out of 6 and "Transportation" with 3 out of 7 (See Table 7.). This indicates a higher level of coherence and technological clarity in the transportation use-cases. Looking into the specific set of technologies, Cluster 1 shows a lower average technology readiness level (TRL) than technologies identified as dominant by members of Cluster 2. Additionally, Cluster 2

[4] The unique identifiers cannot be put into reference to each other. For example, it cannot be said that fuel cells are better than batteries. They can also not be ordered because the matrix includes always the "top" technology per use-case per expert.

[5] Allowing experts to skip single questions complicated the clustering and should, in the future, be avoided if possible.

relies on hydrogen-based technologies in only three use-cases (excluding supply use-cases), whereas Cluster 1 sees hydrogen-based technologies dominant in nine use-cases. Experts from Cluster 1 also believe stronger in the self-reinforcing effect of technology rollouts than those from Cluster 2 and think that the biggest hindrances lay in economic and political reasons (compared to economic and technical reasons for Cluster 2). Based on these findings, we call the clusters Scenario 1 "The Techno-Optimists-Scenario" and Scenario 2 "The Techno-Skeptics-Scenario".

6.2.1. Scenario 1: the Techno-Optimists-Scenario

In the mind of the "Techno-Optimists," the hydrogen supply will be covered with green hydrogen produced with PEM electrolyzers, transported over long distances with hydrogen pipelines, stored in underground facilities, and distributed via existing gas networks repurposed for transport of pure hydrogen by 2035. The identified dominant technologies suggest that "Techno-Optimists" believe in a heavily defossilized world requiring high amounts of hydrogen. Hydrogen pipelines, as well as underground storage in, e.g., depleted oil and gas fields or salt caverns, require high investments and only payout when transported volumes are high (Borsboom-Hanson et al., 2022). Furthermore, the experts' belief in repurposing gas distribution networks suggests that they also believe that natural gas consumption will be reduced to a minimum, hence not requiring the distribution network anymore. In transportation use-cases even the group of hydrogen-progressive "Techno-Optimists" do not believe in the dominance of fuel cells for any private or commercial passenger car but see applications in all other surveyed use-cases. In their scenario, both construction vehicles and heavy-duty trucks will run on hydrogen fuel cells, and bio- and synfuels will find applications in short and medium-haul aviation and large-scale container shipping. Similar conclusions can be seen in the domain of heat/power/industry/feedstock applications. There is no case for hydrogen-based technologies in (retrofit) heating of private and commercial buildings (dominated by heat pumps and teleheating). Still, experts believe in the dominance of hydrogen-based technologies in combined heat and power (CHP), high-grade industrial heat, long-term energy storage, and steel production.

The analysis of potential technological consequences from Delphi 2, see Table 8, allows for similar conclusions. When looking at the topics with the most significant divergence (>10 % difference) between the two expert clusters, ten projections stand out: The "Techno-Optimists" believe that innovation in the hydrogen space is driven by startups (still below 50 %). They also see consolidation in fuel cell- and electrolyzer companies less likely, suggesting they anticipate a greater need for these products. At the same time, the success of business models focusing on supply and demand balancing is rated much higher (15 %), indicating a more pronounced supply scarcity. In the hydrogen supply domain, forming a "hydrogen OPEC" is more likely, which is coherent with the lower expectation of forming a consistent hydrogen trading market. In transportation, an insufficient use penalty is more likely (still only at 22 %), and experts believe that a private buildup of refueling infrastructure for logistics companies might not be necessary.

The most controversial topic among the two groups is whether the shift towards a hydrogen-based economy would lead to a major location shift of high-energy users. For the "Techno-Optimists", there is only a small likelihood of this happening. Housing experts believe stronger in new technology and digitalization solving fossil-energy consumption rather than only efficiency gains due to insulation, denser living, etc. This scenario renders the hydrogen technology field a crucial pillar to the overall defossilization of the world's economic system and sees the positive consequences of shifting towards a hydrogen ecosystem. This aligns with a higher average technological openness of experts from Cluster 1. Analyzing the demographic differences of experts in the two clusters, we found that the experts in Cluster 1 were, on average, German (90 %), Engineers (65 %), and had a background in academia and research (45 %). At the same time, the geographic region and the background were the biggest differentiators between the two groups of experts.

6.2.2. Scenario 2: the Techno-Skeptics-Scenario

The "Techno-Skeptics" foresee that the hydrogen supply will be covered with green hydrogen produced with alkaline electrolyzes (Wappler et al., 2022), transported over long distances with ships in the form of ammonia, stored in ammonia tanks, and distributed admixed in the existing gas networks by 2035. This set of technologies suggests that experts believe in hydrogen playing a role in defossilization, but to a lower extent than in Scenario 1, and relying more on technologies with already higher TRLs. In transportation use-cases, "Techno-Skeptics" only believe in the dominance of fuel cells in heavy-duty trucks, while all other land-based transport is assumed to run on batteries. Additionally, experts believe in fossil dominance in aviation and shipping use-cases. Reliance on proven technologies can also be seen in the domain of heat/power/industry/feedstock applications. They argue that hydrogen-based technologies can only dominate in combined heat, power, and steel production, while all other use-cases rely on existing technologies. This aligns with the fact that experts saw much higher self-reinforcing effects for technologies in this domain, which promotes existing technologies.

For technological consequences (see Table 8), the comparison to Scenario 1 indicates that experts believe innovation in the hydrogen space will come from incumbents, assume a stronger contraction of the number of fuel cell and electrolyzer producers, and believe in less importance of hydrogen supply and demand balancing. In transportation, they believe that 1) an insufficient use penalty is unlikely and 2) a more substantial private involvement in refueling infrastructure will occur. Furthermore, experts believe in the relocation of hydrogen-dependent heavy industries. This scenario perceives the hydrogen technology field as a puzzle piece towards full defossilization but with only a minor role to play in selected hard-to-abate use-cases. These experts favor direct electricity use-cases. Looking into expert demographics, experts in Cluster 2 are German (67 %), Engineers (67 %), and have a background in business/industry (77 %).

6.2.3. Comment-based scenario comparison and quality of scenarios

The analysis and comparison of all expert comments across the two Delphi studies reveal further insights. When looking at the pro arguments for hydrogen usage, the scenarios show differences in the two fields. The Techno-Optimists argue stronger via the social acceptance of hydrogen (e.g., "*Given the current geopolitical situation, I do see the competitiveness of green hydrogen.*"[6]). In contrast, Techno-Skeptics see autarky as a driving scheme for hydrogen. The perspective changes when looking at the con-arguments. Here, the optimists see lock-ins on other green technologies as the most important obstruction. At the same time, the skeptics name missing technology readiness levels and a lack of regulatory support (e.g., "*The green hydrogen market is largely a policy-driven market and tech maturity is missing.*"[7]). Additionally, the technology optimist's belief is stronger in the technological dominance of single technologies – in their case, from the hydrogen technology field – while the skeptics see a world with more technologies coexisting within the application. Overall, these sentiments match the previously described scenarios and strengthen our assumption of a discrepancy between the experts' basic underlying beliefs that formed the two scenarios.

As Kosow & Gaßner (2008) pointed out, the quality of scenarios should be tested against several criteria compiled in a literature review. We use these criteria to gauge the quality of our scenarios. First, we let six experts rate our scenarios along the suggested criteria on a 5-point Likert scale (very poor, poor, acceptable, good, very good) and discuss both the expert input as well as our perspective on the dimension in this

[6] Quote from question on dominances of hydrogen colors (Delphi 1).

[7] Quote from question on dominances of hydrogen colors (Delphi 1).

Table 7
Descriptive statistics for scenario comparison of Delphi 1 (prognosis for the year 2035).

Domain/category	Use-cases/applications (U)	Scenario 1 "Techno-Optimists"			Scenario 2 "Techno-Skeptics"		
		Top Ranked Technology (TPR)[1]	N	TRL[2]	TPR[1]	N	TRL[2]
Supply	Hydrogen production	Green H_2	23	9	Green H_2	9	9
	Electrolysis Technology (decentral)	PEM electrolyzer	23	9	Alkaline electrolyzer	9	9
	Electrolysis Technology (central)	PEM electrolyzer	23	9	Alkaline electrolyzer	8	9
	Long distance transport	Hydrogen pipelines	18	11	Ammonia shipping	9	9.5
	Regional distribution	Repurposing existing natural gas pipeline network for full hydrogen usage	20	7	Admixing in existing natural gas network	6	7
	Long term storage	Gaseous Underground storage	20	6	Ammonia storage	8	11
Transportation	Commercial passenger vehicle	BEV	13	9	BEV and ICE with Diesel or Gasoline	5 + 5	10
	Private intercity passenger vehicle	BEV	12	9	BEV	5	9
	Heavy-duty truck	FCEV	13	7.5	FCEV	5	7.5
	Short-haul commercial aviation (<160 PAX, <2000 km range)	Turbine with mixture of Kerosine/Synfuel/ Biofuel	8	9	Turbine (Kerosine)	5	11
	Medium-haul commercial aviation (<250 PAX, <7000 km range)	Turbine with pure Kerosine or mixture of Kerosine/Synfuel/Biofuel	4	10	Turbine (Kerosine)	5	11
	Construction vehicles	FCEV	12	–	BEV	3	–
	Ocean Container ship	Internal combustion engine (bio- or synfuel)	11	9.5	Internal combustion engine (diesel/oil)	4	11
Heat/power/ind./ feed	Retrofit private home heat	Electric heat pump	5	10	Electric heat pump	3	10
	Retrofit residential housing/office heat	District heating (teleheating)	5	11	Electric heat pump	2	10
	Decentral industrial heat (high grade)	Hydrogen burner	5	–	Natural gas burner	2	–
	Combined heat and power plants (CHP)	Hydrogen turbine	5	–	Hydrogen fuel cell	3	–
	Long-term energy storage	Power-to-gas-to-power	5	–	Pumped Hydro	3	–
	Primary steel production	DRI-EAF with hydrogen	5	5	DRI-EAF with hydrogen	3	5

(1: Removal of TPRs when $N = 1$ to treat outliers, two technologies when ranking equal; 2: Technology Readiness Level derived from IEA ETP Clean Energy Technology Guide, "–" for technologies not shown in guide (IEA, 2022); FCEV = fuel cell electric vehicles; BEV = battery electric vehicles.)

Table 8
Descriptive statistics for scenario comparison of Delphi 2.

Domain/category	Abbreviation of topic	Probability means			Impact means		Desirability means		Evaluation dimension
		Scenario 1 "Techno-Optimists"	Scenario 2 "Techno-Pessimists"	Δ	Sc. 1	Sc. 2	Sc. 1	Sc. 2	
General	Energy cost trend	Sligh incr.[1]	Significant incr.[1]	–	–	–	–	–	5-Point Likert
	Regional dominance	China[2]	Europe[2]	–	–	–	–	–	Ranking of answers
	Technology Openness	50 %	58 %	8%p	4.1	4.3	3.7	4.7	P, I, D
	Seasonality of energy cost	46 %	48 %	2%p	2.8	4.0	2.2	3.0	P, I, D
	Electrical path dependency	62 %	68 %	6%p	3.7	4.0	2.2	3.3	P, I, D
	Startup innovation	40 %	30 %	10 %p	3.8	3.3	3.0	3.3	P, I, D
	Market consolidation	49 %	63 %	14%p	4.3	3.0	2.6	3.3	P, I, D
	Cross sectorial clusters	70 %	65 %	5%p	3.7	3.0	3.8	3.7	P, I, D
	Impact on the labor market	28 %	28 %	0%p	4.2	4.5	1.8	1.0	P, I, D
	Balancing business mod.	70 %	55 %	15%p	3.6	3.3	3.6	2.7	P, I, D
Production	Supply-side dominance	Today's O&G[2]	Today's O&G[2]	–	–	–	–	–	Ranking of answers
	The promoter of green hydrogen	43 %	42 %	1%p	3.8	2.7	3.1	2.7	P, I, D
	Replacing OPEC	49 %	38 %	11%p	4.2	3.7	2.6	2.0	P, I, D
	Global trading market	64 %	78 %	14%p	3.8	3.3	3.5	3.7	P, I, D
	Green H_2 certification	76 %	82 %	6%p	4.0	3.0	4.2	4.3	P, I, D
	Decentral or central H_2	36 %	42 %	6%p	3.7	3.7	3.1	2.7	P, I, D
Transportation	Inefficient use penalty	22 %	10 %	12%p	3.8	3.5	3.5	2.3	P, I, D
	Technological interdependencies	–	–	–	–	–	–	–	Influence on other use-case
	Logistics H_2 infrastructure	41 %	55 %	14%p	4.0	4.0	3.1	3.5	P, I, D
Heat/power/ind./ feed	Diversification of H_2 producers	58 %	65 %	7%p	4.3	4.0	3.8	4.0	P, I, D
	Location shift of heavy industry	35 %	85 %	50 %p	4.0	4.0	3.0	4.0	P, I, D
	Efficiency vs. technology	58 %	85 %	27%p	3.0	3.0	3.5	4.0	P, I, D
	Symbiotic digitization	78 %	55 %	23%p	3.8	3.0	4.5	3.0	P, I, D

(1: here the dimension is not "probability" but a 5-Likert from 1 = significantly increase to 5 = significantly decrease, 2: here the dimension is not "probability" but the top-ranked answer, P,/I/ D = Probability/Impact/Desirability.)

regard. Appendix H shows all expert answers. Experts ranked the "plausibility" as "very good" and pointed out that the scenarios can be seen as possible from today's perspective. No individual criteria exist that would render the scenarios unattainable from a technological point of view. Similar is valid for the "consistency". Scoring "very good" again, the scenarios are not mutually exclusive since they both mark manifestations of possible development on two positions of the same scale. Here, experts highlighted the aspect that one scenario assumes some technologies reach technological readiness faster than others.

> "Optimistic scenario comes with more efficient but less proven technology approaches (e.g., PEM or H_2 pipelines) while skeptic scenario with more proven approaches (e.g., alkaline or ammonia)."[8]

Experts perceived the scenarios as "very good" in "comprehensibility and traceability" and mentioned the right level of detail without overloading in complexity. The perceived "distinctness" is seen as "very good"; however, experts point out that in some applications and use cases, the scenarios overlap in the sense that the solutions ranked dominant are either the same or could co-exist. We agree with this view but point out that the distinctness is not defined by the similarity in each use-case but by the set of technologies dominating the different use-cases. We also asked the experts to rank the "transparency" of our scenarios. The six selected experts ranked the scenarios as "very good" in this dimension. The "degree of integration" was also perceived as "very good", and experts praised our approach to disentangle technological dominances from their societal, political, and economic consequences and create a perspective on the full value chain in one consistent study. The "quality of reception" scored a "good". Experts pointed out the complexity of the scientific description of the method and the academic presentation of the data, which makes the reception more difficult.

7. Discussion

Our theory and evidence on the future of hydrogen as an interconnected technology field have several meaningful implications for research, practice, and policy.

7.1. Implications for research

First, we complement existing Delphi studies on hydrogen (e.g., CIFS, 2021; Lee et al., 2022; Thoennes and Busse, 2014) by shifting the focus from individual hydrogen technologies examined in isolation to hydrogen as an integrated technology field. This technology field comprises distinct technologies that complement each other along the hydrogen value chain (production, storage, transport, and use) and compete with other non-hydrogen technologies for dominance in distinct application areas ranging from road traffic and aviation to heating and industrial applications. This approach is consistent with theoretical advances in technology strategy (e.g., Kapoor and Klueter, 2021), technology diffusion (e.g., Anderson and Tushman, 1990), and especially technology interactions (e.g., Sandén and Hillman, 2011) that highlight the interplay between distinct technologies—be they competitive, symbiotic, or parasitic—as a critical yet underexplored factor shaping technology diffusion.

As we show, a field-level perspective that seeks to account for the multifaceted nature of technology interactions within and between technology fields can yield novel insights on the future diffusion of hydrogen that cannot be generated by conventional approaches focusing on individual technologies. With regard to within-field technology interactions, for instance, our study points to the importance of specific technology bundles or technology mixes such as those seen in Scenario 1. We can see a dependence between the proliferation of hydrogen transported over long distances with hydrogen pipelines and the ability to store it in vast quantities in underground facilities. Another connection is between PEM electrolyzers and the various applications of fuel cells in different use cases (HDT, ferries, etc.; also compare Section 5.2.). These bundles leverage technological complementarities essential for propelling hydrogen diffusion and eventual dominance in key application areas, such as land-based transport (vehicles, trucks, etc.). Our study highlights the critical role of path dependencies and lock-in effects for between-field technology interactions that could lead to "the-winner-takes-it-all" outcomes in some application areas. In passenger transportation and heating, competing non-hydrogen technologies – such as battery-electric drive trains and heat pumps – are projected to benefit from such effects. They are fueled by higher technology readiness levels, greater compatibility with existing infrastructure, and higher initial adoption levels, arguably leaving little space for hydrogen solutions in these application areas.

Second, we demonstrate the viability of adapting Real-Time Delphi approaches to create foresight on the effects of technology interactions within and between technology fields and on technology diffusion more generally. In particular, our adapted Delphi approach enables researchers and practitioners to create scenarios about future technology mixes solely based on Delphi survey data and thus does not require a multi-method approach or mapping out an exhaustive list of underlying drivers. Staging two interconnected Delphi studies allows research to analyze the interaction of causes (technology dominance and hindrance reasons) and events (technology consequences). Overall, this approach could help researchers and practitioners in areas other than hydrogen to leverage the potential of the Delphi method to zoom in on technology interactions within and between fields and better understand the implications of such interactions for the diffusion of individual technologies and the broader technology field they are part of.

7.2. Implications for managerial practice and policy to advance hydrogen-based technologies

The results of our Delphi study are important for political actors, as the transition to hydrogen presents both opportunities and challenges for national economies (Eicke and De Blasio, 2022; Noussan et al., 2021). Previous research anticipates that this transition will lead to market dynamics where energy-dependent economies might achieve energy autonomy or even ascend to become net hydrogen exporters (Eicke and De Blasio, 2022; Noussan et al., 2021). Vice versa, high-consumption countries face the risk of deepening dependencies, setting the stage for new geopolitical tensions (Eicke and De Blasio, 2022; Noussan et al., 2021). Political actors must prepare for upcoming changes to navigate the hydrogen transition effectively. Thus, they could use our future scenarios to develop strategies to shape political measures.

Our research showed that different technology mixes could power the future of hydrogen. However, bringing these technologies to market readiness in time to reach dominance in 2035 would require further development. Promoting a specific technical solution is also a decision against promoting its alternative. Our scenarios provide clarity in this regard, and they can help decide where to focus (enhance and scale back) public and private investment efforts to develop the most needed hydrogen-based technologies for each application.

In the value chain step "hydrogen supply", we found the two scenarios to disagree on the technology mix but not on the fact that green hydrogen will dominate in 2035, which is also in line with global forecasts (IEA, 2021b). This suggests that greater technological openness is required since a dominant technology is not yet apparent. We found multiple reasons for this phenomenon: The differences in perceived hydrogen proliferation in consumption use-cases influence the supply-side technology mix. We argue that this derives from varying assumptions on future demand and potential interdependencies between fuel cell and electrolyzer technologies. Additionally, experts believe in low path dependencies and found the co-existence of technologies to be likely. Based on this, we recommend policymakers to equally pursue different electrolyzer technologies, means of transport, and distribution technologies for green hydrogen.

Based on our results in consumption use-cases, the proliferation of hydrogen-based technologies for defossilizing land-based transport applications is unlikely, which opposes the view of the Hydrogen Council (2020, 2021) but is in line with the forecast of the IEA (2021b). An exception is only the case of heavy-duty trucks. Even the group of

[8] Quote from post-Delphi scenario quality survey.

hydrogen-progressive "Techno-Optimists" does not believe in the dominance of fuel cells for any private or commercial passenger cars. This finding disqualifies the technology from playing a major role in defossilizing transport.[9] This is especially the case because experts believe transportation use-cases are prone to be dominated by one single technology (e.g., battery electric passenger cars) due to higher path dependencies as it benefits from mass production and existing infrastructure. This will not even change if fuel cell electric heavy-duty trucks become dominant because experts expect low inter-use-case benefits (low technological interdependency). Based on this, efforts to bring fuel cells to wide use in land-based transport other than trucks should be limited. This saves resources for alternatives with greater economic and defossilization potential.

A similar conclusion is valid in (retrofit) private and commercial heating use-cases, where hydrogen-based technologies are not expected to become dominant. For these use-cases experts believe in heat pumps and teleheating, both of which show higher technological readiness levels, have (partially) existing infrastructure, are expected to have lower running costs, and are already used today. This finding suggests that hydrogen networks supplying private and commercial housing for heating purposes are unnecessary, and funding and research efforts in this field can thus be reduced.[10]

A less clear case is seen in aviation and maritime use-cases. Here, both scenarios settled on the currently dominant technologies of propulsion (turbines and internal combustion engines). Still, experts had different views on fuel powering these engines (mixtures or pure bio- and synfuels against fossil-based fuels). Hence, to defossilize quickly, research and market activity should focus on the technologies that can provide sufficient syn- and biofuels to the market. In this case, fossil fuels can be replaced gradually, allowing the reuse of existing fueling infrastructure and vessels.

The picture differs for industrial applications (combined heat and power, high-grade industrial heat, long-term energy storage, and steel production). Here, we can see the dominance of H_2-based technologies in both scenarios. This suggests that hydrogen should be promoted in these applications and that hydrogen networks (at least in 2035) can be limited to large-scale industrial consumers, reducing the necessary infrastructure build-up. The study thus highlights the significant role of hydrogen within the industrial sector. To maintain national industry competitiveness, political actors should implement strategies that ensure a reliable energy supply and decrease reliance on energy imports. Actions include boosting domestic hydrogen production or diversifying the sources of energy imports through international collaborations. In addition, the findings from the study can be used to support the design and development of education and training programs for hydrogen technologies aiming to nurture a skilled workforce for the emerging technology sectors.

Overall, according to our panel, in 2035 hydrogen will play a significant role in global defossilization but will do so primarily in replacing today's grey hydrogen and venturing into industrial and power applications. The substantial uptake in other hydrogen-based use-cases potentially falls into a later period or misses the infliction point for proliferation. The study also underscores the necessity for a holistic environmental and climate policy, as it reveals that the dominance of green technologies varies by use-cases. To realize a sustainable transition, political actors should choose a multifaceted approach and promote green technologies according to their most suitable use cases.

7.3. Limitations and further research

Our work is not free of limitations that arise from two dimensions: the hydrogen technology field and the Delphi method. First, while Delphi is a powerful method, we are also aware of its limitations, as the uncertainty of the future is not measurable and is not foreseeable. As Derbyshire (2017) highlights that subjective probabilities in the Delphi method are based on experts' individual experiences and knowledge. Thus, they might not accurately reflect the uncertainty about the future, as each expert may have different perspectives and biases. Additionally, using numbers and probabilities can lead to an overreliance on seemingly precise forecasts. This might result in underestimating the variety of possible future events and neglecting highly impactful but less probable events.

Second, the solely on Delphi-data-grounded scenario approach needs validation. To the best of our knowledge, no previous research has used a similar approach to create foresight in technology fields, and we suggest evaluating our methodological procedure in other research settings to validate our approach further. Other researchers could apply this technique in another setting where a multitude of competing and complementing technologies interplay and thus form a broad technology field. These could include "artificial intelligence", "human space exploration", "personalized medicine", "3D printing", and more.

Third, our research relied on a panel overrepresented by German experts. The cluster of techno-optimists, in particular, had a significantly higher share of experts from Germany. It seems natural to be more optimistic in Germany. The country has a solid national hydrogen strategy with associated media reporting generous incentivization schemes (Gül et al., 2019) and is dependent on energy imports. This is an important finding and a limitation of the study since overrepresentation can lead to unbalanced results. Especially since positive feedback-enhancing environment could function as an "echo-chamber", limiting technology openness and thus biasing decision-makers to identify optimal technologies.

Regarding future research avenues, some of the findings reported in the study are either controversial or could not reach consensus while being perceived as highly relevant for the future of the hydrogen technology field. We are convinced further research on these questions is necessary. Similar is valid for the finding that experts' arguments for hydrogen were more often placed on a socio-economic level. In contrast, arguments against hydrogen were situated on the use-case level. This poses a significant threat to the roll-out of hydrogen-based technologies because system-level advantages do not pay out directly to end-users. We expect actors introducing these technologies to decide based on benefits for their specific case, which would mean they do not optimize overall system performance. We are convinced that further analyzing this phenomenon specifically for hydrogen-based technologies is of interest from a policy perspective. Lastly, our study found that actual domain experts were always more skeptical regarding green technologies' dominance in their field than "adjacent" experts. We were further able to show that experts translated their expertise with a specific technology (based on their use-case) to the application of the same technology in other use-cases where, again, they were more skeptical. We suggest studying this effect of expert-skepticism and its influence on technology forecasting in other research settings. Related to this, we found the projection "Location shift" to be highly debated among the experts and answered diametrically differently between the two scenarios. The suggested potential emigration of energy-intensive industries poses a threat to regions with solid manufacturing footprints and low energy resources (such as Germany). We state that a deeper understanding of the underlying drivers is necessary, potentially through applying our research approach in other similar geographical settings.

[9] In 2020, 5.6 Gt of almost 8 Gt of CO_2 emissions stemmed from road transport (IEA, 2021a), where passenger car transport produces 45.1 % of all transport emissions (CO2 Transport Emissions - Our World in Data, 2018).

[10] This view opposes the forecast of the IEA (2021) but is supported by doubts about the cost-competitiveness of hydrogen technologies by the Hydrogen Council (2021) and Liebreich (2021).

Author statement

We the undersigned declare that this manuscript is original, has not been published before, and is not currently being considered for publication elsewhere. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We understand that the Corresponding Author is the sole contact for the Editorial process. He is responsible for communicating with the other authors about progress, submissions of revisions, and final approval of proofs.

CRediT authorship contribution statement

Leo Leypoldt: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christina Dienhart:** Writing – review & editing. **Hüseyin Caferoglu:** Writing – review & editing, Supervision. **Torsten-Oliver Salge:** Writing – review & editing, Validation, Supervision, Funding acquisition. **David Antons:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition.

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

The authors do not have permission to share data.

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Appendix A. Overview short listing logic for use-cases

Step	Question	Source for evaluation	Type of criterion
1	Is there still a battle for technological dominance?	Expert interviews and desk research	If "YES" proceed to 2
2	Is the potential amount of consumed hydrogen relevant in comparison to total hydrogen production?	Forecasts of IEA and Hydrogen council and expert interviews	If "YES" include in survey If "NO" proceed to 3
3	Is the use-case relevant for overall defossilization (i.e., no green alternative)?	ETP Clean Energy Technology Guide	If "YES" include in survey If "NO" proceed to 4
4	Is the hydrogen value chain reflected entirely?	n/a	If no other application from category is in short list include in survey If yes disregard

Appendix B. Coding table comment analysis (quote-level only exemplary)

Theme	Topic	Example quotes
Arguments favoring hydrogen-based technology	Reuse of assets and/or infrastructure	*"Due to the installed conversion facilities a lock-in effect is created. Also, switching to other carriers (in shipping) needs investments."*
	Flexibility	*"Using drop-in decarbonized fuels makes shift to full usage easier than other alternative fuels like LH_2."*
	Social acceptance	*"For grey [hydrogen] societal acceptance for heavy climate burden is shrinking fast."*
	Economies of scale	*"Investments into green hydrogen drives down costs for green hydrogen (learning by doing). Decreased costs for green hydrogen makes switching to other technologies more costly (in terms of opportunity cost)."*
	Autarky	*"If the geopolitical situation [Russia/Ukraine conflict] continues over the next 10 years (any situation that constantly raises gas and oil prices) and policymakers might this window of opportunity to significantly scale up RES supply."*
	Sector coupling	*"P2X allows for the most end-use flexibility.,* i.e., *full sector coupling instead of power-system internal transformations."*
Arguments against hydrogen-based technology	Lock-in on other technologies (due to late ramp-up)	*"Charging infrastructure creates lock-in on BEVs. BEV is taking over already today, H_2 infrastructure is way behind, and BEV will take it all."*
	Missing regulatory support	*"[There is] no regulatory framework for hydrogen in gas network."*
	Technology readiness level (products not available, market ready)	*"Except for pipeline none of the above listed technology has a high TRL (technology readiness level) today."*
	Efficiency	*"For P-x-P applications the overall efficiency is too low to be economical for on scale use."*
	Hydrogen needed for otherwise hard to abate sectors	*"H_2 is just too valuable to be used for residential heating, and too complicated and expensive to implement, and also very inefficient."*
	Costs	*"In my understanding, the higher cost of H_2 from electrolysis is by far the highest obstacle."*
Precondition for green hydrogen economy	Low-cost renewable energy	*"Since green electricity is the main cost driver for green hydrogen, projected future price decreases imply significant economic benefits compared to other colors."*
	Abundant renewable energy	*"The switch to green hydrogen will require additional capabilities in RES."*

(*continued on next page*)

(*continued*)

Theme	Topic	Example quotes
Level of technological openness	Path dependency towards single technology *(tracked per use-case)*	*"Whatever technology becomes ready first will become dominant because than infrastructure investments will be made. Thus lock-in is created!"*
	Co-existence of technologies *(tracked per use-case)*	*"BEV will do the job for most applications,* fuel cell electric vehicles *second, catenary will be a thing in some regions, bio-/syn- fuels will play a role in places with less charging infrastructure."*

Appendix C

C.1. Dissent and sentiment analyses – method in Delphi 1

We analyzed the study from the viewpoint of different stakeholder groups. We split experts into three groups: Experts with a background in "Hydrogen Supply", experts with a background in "Consumption – Transportation", and experts with a background in "Consumption – Heat/Power/Feedstock/Industry". We clustered the latter four groups in one group since many experts specified being active in multiple of these fields. Motivated by Beiderbeck et al. (2021a) and Spickermann et al. (2014), we measured experts' underlying personality traits to understand their "voting behavior" better. Thus, at the end of the survey, experts were asked to rate their confidence in their answers on a 5-point Likert scale for each value chain category. Additionally, we requested to answer an abbreviated questionnaire to test for individual "Resistance to Change" and "Openness". From this, we built a proxy to control for technological openness of the experts. We leaned on a validated approach by Oreg (2003) but shortened the proposed survey to account for experts' limited available time span. Both factors ("Confidence" and "Technological Openness") were used to calculate Spearman rank correlations with the technology rankings in use-cases.

C.2. Dissent and sentiment analyses – results of Delphi 1

In the stakeholder group analysis (split by activity in value chain steps), we found group differences are slight but distinct in selected projections. In these cases, the actual category experts (e.g., transportation experts for transportation use-cases) are always more skeptical regarding green technologies' dominance in their field than "adjacent" experts. We saw robust results for use-cases in the domain "supply", indicating that experts from various value chain backgrounds see the production and distribution of hydrogen the same way. The only slight difference occurred in "Long-term storage", where experts with a background in mobility applications ranked storage in the form of hydrocarbons higher than in the form of ammonia. This picture is coherent since many transportation applications would rely on hydrogen in the form of hydrocarbons (e.g., synfuels). In the use-cases in the category "Consumption – Transportation", again, the first ranks are robust and, in the majority, depending on the stakeholder group. However, for heavy-duty trucks, "supply" experts believe in BEVs (battery electric vehicles) as the best alternative. In contrast, the specific category experts (Consumption – Transportation) argue that combustion engines run on diesel, and experts from the background of heat and power think biofuels are the next best alternative. Similar is valid for medium-haul aviation, where heat and power experts believe stronger that turbines run on mixtures of kerosine and syn-/biofuels. In "Short-haul aviation", experts from transportation as well as heat and power see battery-driven flight as dominant, whereas hydrogen production experts believe in turbines run on mixtures (kerosine, bio-/synfuels). The most considerable divergence can be seen in high-grade industrial heat, where "supply" experts argue for hydrogen burners, transportation experts believe in biogas burners, and people from the heat and power segment think natural gas will still dominate. Similar holds for CHP (combined heat and power), where both transportation and supply experts believe in hydrogen turbines' dominance. In contrast, experts with heat and power backgrounds are prone to choose fossil-powered steam turbines.

Looking into sentiment analysis – through analysis of experts' level of confidence (LoC) – we can show that experts also translate their expertise (based on technologies in their field) to technological solutions in other fields and are again more skeptical within these. We calculate the spearman rank correlation between the rank for each technology per use-case and the three distinct LoCs per category. We could not find any technology-LoC-combination with p-values below 0.01. However, seven are significant at $p < 0.05$, of which we discuss 5 in detail.

First, LoC in transport applications shows a positive rho to the rank of hydrogen combustion engines in passenger vehicles. This indicates that experts confident in transport applications are less likely to believe in this technology. The same can be seen for this technology in applying heavy-duty trucking and construction vehicles. Second, the LoC in heat, feedstock, and industry applications show a positive rho for the interaction with fuel cell as well as turbine-powered short-haul aviation (run on liquid hydrogen). Indicating that the experts confident in this area believe stronger in the proliferation of these technologies.

Lastly, we calculate the spearman rank correlation between the rank for each technology per use-case with the experts' overall "Technological Openness". We found significance at $p < 0.05$ for four correlations: internal combustion engine powered with hydrogen in passenger cars (positive rho), fuel cell driven medium-haul aviation with liquid hydrogen (positive rho), hydrogen fuel cells in CHP plants (positive rho), and latent heat in long term energy storage (positive rho). All show a lower ranking with increasing tech openness for the two respective technologies. All tech solutions are at a low technological readiness level in their specific use-case, showing that even with higher technological openness experts do not become "naïve" to believe in technological feasibility until 2035. We can only describe the correlations for all these statements and must speculate about the causality to a certain extent.

Appendix D. Interdependency matrix of projections and use-cases (abbreviated to show only projections and use-cases selected for the Delphi study)

Projection/ use-case	Hydrogen production	Electrolysis Technology (decentral)	Electrolysis Technology (central)	Long term storage	Long distance transport	Regional distribution	Commercial passenger vehicle	Heavy-duty truck	Medium-haul commercial aviation	Ocean Container ship	Private intercity passenger vehicle	Short-haul commercial aviation	Construction vehicles	Retrofit private home heat	Retrofit residential housing/ office heat	Decentral industrial heat (high grade)	Combined heat and power plants (CHP)	Long term energy storage (e.g., seasonal)	Primary steel production
Energy cost trend	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Regional dominance	x	x	x	x	x	x	x	x		x	x	x	x	x	x		x	x	
Technology Openness	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Seasonality of energy cost							x	x	x	x	x	x	x	x	x	x	x	x	x
Electrical path dependency							x	x	x	x	x	x	x	x	x	x	x	x	x
Startup innovation	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Market consolidation	x	x	x			x	x	x		x	x	x	x	x	x		x	x	
Cross sectorial clusters	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Impact on labor market	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Balancing business mod.	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Supply side dominance	x	x	x	x	x	x													
Promoter of green hydrogen	x	x	x	x	x	x													
Replacing OPEC	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Global trading market	x			x	x	x													
Green H_2 certification	x	x	x	x	x	x													
Decentral or central H_2	x	x	x	x	x	x													
Inefficient use penalty							x	x	x	x	x	x	x	x	x	x	x	x	x
Technological interdependencies							x	x			x		x						
Logistics H_2 infrastructure								x											
Diversification of H_2 producers	x	x	x	x	x	x										x	x	x	x
Location shift of heavy industry	x	x	x	x	x	x										x	x	x	x
Efficiency vs. technology														x	x				
Symbiotic digitization														x	x				

Appendix E. Descriptive statistics for Delphi 2 with medians instead of means

Abbreviation	N	Probability median	Impact median	Desirability median	Dominant selection	Evaluation dimension
Energy cost trend	29	2				5-Point Likert
Regional dominance	27				Europe	Ranking of answers
Technology Openness	29	50–60 %	4	4		P, I, D
Seasonality of energy cost	30	50–60 %	3	3		P, I, D
Electrical path dependency	30	60–70 %	4	3		P, I, D
Startup innovation	30	30–40 %	4	3		P, I, D
Market consolidation	27	60–70 %	4	3		P, I, D
Cross sectorial clusters	29	60–70 %	4	4		P, I, D
Impact on the labor market	28	20–30 %	4	1		P, I, D
Balancing business mod.	28	50–60 %	3	3		P, I, D
Supply-side dominance	23				Today's O&G majors	Ranking of answers
The promoter of green hydrogen	26	60–70 %	3	3		P, I, D
Replacing OPEC	25	60–70 %	4	2		P, I, D
Global trading market	25	60–70 %	3	3		P, I, D
Green H_2 certification	26	80–90 %	3	4		P, I, D
Decentral or central H_2	25	30–40 %	4	3		P, I, D
Inefficient use penalty	24	20–30 %	4	3		P, I, D
Technological interdependencies	25					Influence on other U
Logistics H_2 infrastructure	23	50–60 %	4	3		P, I, D
Diversification of H_2 producers	17	60–70 %	4	3		P, I, D
Location shift of heavy industry	19	50–60 %	4	3		P, I, D
Efficiency vs. technology	20	30–40 %	3	3		P, I, D
Symbiotic digitization	20	60–70 %	4	4		P, I, D

Appendix F

F.1. Dissent and sentiment analyses – method in Delphi 2

During Delphi 2, we specifically asked experts to rate the desirability to control for a potential desirability bias since other research showed that probability and desirability often correlate (Ecken et al., 2011). We calculated spearman rank correlation coefficients between the two dimensions. Additionally, we analyzed our dataset of Delphi 2 for potential bi- or multimodal distributions via a visual inspection of histograms. This approach ensures that a missing consensus is not deriving from two or more opposing groups (Beiderbeck et al., 2021b; Dajani et al., 1979). Additionally, we ran the value-chain-based stakeholder group analysis and the sentiment analysis on technological openness and experts' confidence, like in the first Delphi.

F.2. Dissent and sentiment analyses – results of Delphi 2

Analyzing the desirability bias, we found that 17 out of 19 projections showed a positive slope, but only in one projection the positive slope was significant, at a 99 % level ($p < 0.01$). We calculated adjusted probability values for this projection along the method of Ecken et al. (2011) and found that even with adjusted probability values, the consensus (in this case, missing consensus) did not shift. Based on that, we decided not to control for a desirability bias.

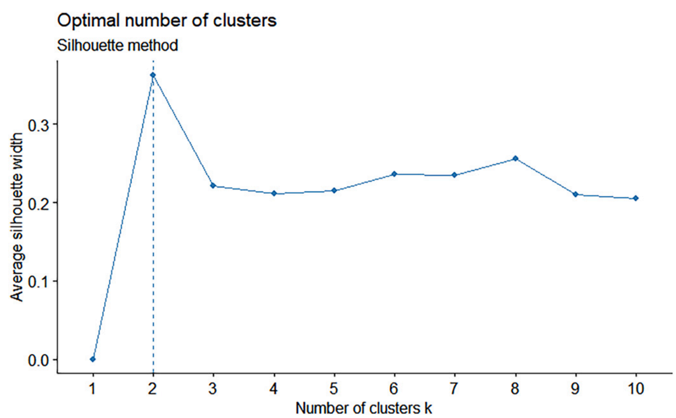
During the bipolarity analysis, we found three projections with a bimodal distribution of answers, all dissenting in the descriptive statistics. We can, therefore, assume that the bimodal distribution is the cause of this dissent. For all three projections, "Technology Openness", "Seasonality of energy cost", and "Location shift", we find one mode below 50 % probability and one mode above, indicating that experts think diametrically differently. The first and the third projections also show high average values of the impact dimension, thus making them specifically relevant to the hydrogen firm ecosystem and highly debated.

For the value chain-based stakeholder group analysis, the results of the second Delphi mirror those of Delphi 1. Category experts tend to be more skeptical regarding green technologies' dominance in their field than "adjacent" experts. For the projection "energy cost trend", experts from the heat and power segment expect higher cost increases than others. Experts from a transportation background are especially prone to believe in Chinese dominance within the "Regional dominance" projection. This means significant Chinese exports of fuel cells. At the same time, other equipment like hydrogen turbines, electrolyzers, and equipment required to produce hydrogen derivatives would still be seen as dominated by European suppliers. This is notable, especially in comparison to the "impact on the labor market", where experts from the transportation sector believe in a stronger negative impact. In another projection on the seasonality of energy costs, experts from today's heat and power segment tend to believe in low seasonality. In contrast, hydrogen and transportation experts (the latter less the former) tend in the other direction. Additionally, experts from the transport segment believe in a lower probability of a "penalty tax" disincentivizing use-cases for hydrogen with lower defossilization potential. These experts also rate this projection as less desirable since it would mainly hurt hydrogen consumption in many transportation use-cases. These experts also believe in a much stronger positive influence of fuel cell dominance in heavy-duty trucks on other transportation applications, making the exception from the identified pattern of increased tech skepticism within their domain and category.

The phenomenon of experts being more skeptical of their own segment of the value chain also holds in the confidence level analysis. For the projections of Delphi 2, we calculated spearman rank correlations between probability and level of confidence. None of the projections correlated at a 99 % significance level ($p < 0.01$), but five projections were significant at 90 %-level ($p < 0.1$). Three of which were close to the 95 % level. For the projection "Decentral or Central H_2", we found a positive correlation between LoC-supply and probability at $p = 0.05$, indicating that experts' confidence in hydrogen production and distribution believe stronger in decentral production of H_2 than experts less confident in this field. For the projection "Replacing OPEC (Organization of Petroleum Exporting Countries)", we found a negative correlation between LoC-transportation and probability at p = 0.05. This implies that experts with high confidence in H_2 transportation applications expect a lower probability that a new "Hydrogen-OPEC" will be established by 2035. Lastly, we found a negative correlation between LoC-Heat/Power/Industry/Feedstock and the probability for the projection of "Startup innovation". This shows that experts confident in the heat and power segment believe the most substantial innovation to come from today's incumbents rather than new companies. This might derive from the fact that companies in this part (heat and power) of the value chain historically faced only a low number of disruptors (Żbikowski and Antosiuk, 2021).

In the last step, we calculated spearman rank correlation coefficients for the average technological openness and the probability for each projection. We found three projections with correlations significant at $p < 0.05$ (Technology Openness, Market consolidation, Green H_2 certification). We found a negative correlation for two of those, meaning experts rate the probability higher when tech openness is low. This means tech-open experts believe stronger in a regulation that is not technologically open, think that market consolidation among FC and electrolyzer producers is less likely, and rate probability lower that a market for green H_2 certification will evolve. Again, we can only describe the correlations for these statements and must speculate about the causality.

Appendix G. Silhouette graph for identifying the number of clusters



Appendix H. Expert responses on scenario quality

		Expert					
Quality criteria	Median	A	B	C	D	E	F
Plausibility	5	5	5	5	5	5	5
Consistency	5	5	5	5	4	4	5
Comprehensibility & traceability	5	5	4	5	3	5	5
Distinctness	5	4	4	5	5	5	5
Transparency	5	5	5	5	3	4	5
Degree of integration	5	5	n/a	5	3	n/a	5
Quality of reception	4.5	4	4	5	5	5	4

Scale: 5 = Very Good; 4 = Good; 3 = Acceptable; 2 = Poor; 1 = Very Poor, n/a = Not answered.

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