

Secondary Publication



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Date of secondary publication: 13.03.2026

Version of Record (Published Version), Article

Persistent identifier: urn:nbn:de:bvb:473-irb-114262x

Primary publication

Schwappach, Daniel; Faix, Werner G.; Mergenthaler, Jens; Carbon, Claus-Christian (2026): Developing an Ecosystem Framework for Green Hydrogen Scale-Up : A Contribution to Innovation Leadership, in: Journal of the knowledge economy, Berlin ; Heidelberg ; New York, NY: Springer, Vol. 17, No. 1, pp. 1694–1725, doi: 10.1007/s13132-024-02376-z.

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Developing an Ecosystem Framework for Green Hydrogen Scale-Up: A Contribution to Innovation Leadership

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Received: 9 August 2023 / Accepted: 26 August 2024 / Published online: 22 March 2025
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Abstract

Global warming due to greenhouse gas emissions (GHG) caused by humankind and the debate about energy security in Europe due to ongoing political and bellicist conflicts, as well as a high mass-related energy density and already well-developed technologies, make green hydrogen¹ from renewable resources one of the promises of salvation. Green hydrogen is on the edge of moving to industrial scale, from innovation to business. Ecosystem theory can help leaders to shape this transition. An explorative qualitative descriptive study design was chosen for the research of the joint value creation, emergence, and ecosystem archetypes as it is needed for describing the object, the green hydrogen ecosystem (GHE). We interviewed 22 experts utilizing a semi-structured interview guide. The data were systematically analyzed by qualitative content analysis. Decarbonization is set as an objective to be achieved through joint value creation of the GHE by providing green hydrogen continuously in the appropriate quantity, with the corresponding price, at the desired location, and at the right time. The innovation ecosystem must be transformed into a business ecosystem with the objective of reducing the risk for all actors.

Keywords Ecosystem · Hydrogen · Innovation · Leadership · Management · Climate change

JEL Classification Codes O13 · O3 · P48 · Q21 · Q28 · Q4

¹Green hydrogen is defined by the use of renewable energy with low to no greenhouse gas emissions according to Gribova and Giese (2021).

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Introduction

Global warming caused by human activities is progressing from pre-industrial times at about 0.8 to 1.2 °C. Between 2030 and 2052, the current rate expects an increase of at least 1.5 °C against the pre-industrial scale. Anthropogenic greenhouse gas emissions (GHG), especially carbon dioxide (CO₂), have contributed significantly to climate change since pre-industrial times (Masson-Delmotte et al., 2018). The Paris agreement, adopted by 195 countries at the 21st Conference of the Parties (COP21) in December 2015, targets keeping climate change below 2 °C, ideally to 1.5 °C (European Commission 4/22/2022). The European Union and its member states have set the binding objectives of a net decrease of at least 55% in GHG emissions by 2030 compared to 1990 and a net zero by 2050 (European Commission 2019). In addition to climate change, conflicts all over the planet, including the 2022 Russian invasion of Ukraine, have dramatically changed the perspective of global energy security, especially in Europe. Energy embargoes against Russia demand a faster transition to alternatives and renewable energy sources to become independent from Russian oil, coal, and gas (bdew, 2022). As a consequence, the transition to green hydrogen based on renewable energies is to be accelerated according to the plan REPowerEU (European Commission 8/4/2022).

Green hydrogen technology seems to be on the verge of an industrial breakthrough. By early 2021, over 30 countries have announced hydrogen roadmaps and governments worldwide have committed more than \$70 billion dollars in public investment. The industry has committed to more than 200 hydrogen projects and ambitious spending targets (Hydrogen Council and McKinsey & Company 2021). In 2020, 90 million tons of hydrogen mainly from fossil fuels were consumed (IEA—International Energy Agency 2021). Worldwide figures show the increase of current operating electrolyzer production capacities from 0.2 GW (2021) to more than 340 GW in 2040 (AURORA Energy Research 2021b). This will increase capacity by a factor of 1700. The current average project size is between 1 and 10 MW and the first large orders are also already being placed. We might expect a strong increase of the average project size to 100–500 MW by 2025 and 1+GW by 2030 (AURORA Energy Research 2021a). Green hydrogen can be used for the production of e-fuels, for example (Agora Energiewende, 2018). To compete with gasoline, an increase in gasoline prices would be necessary. A study by Zafeiriou et al. (2014) shows that the cost of gasoline in the period before 2014 did not depend on other energy commodity prices and gas emissions but rather on speculation on the oil markets. This equation would change if carbon dioxide certificates were to increase the cost of gasoline. In agriculture, for example, there is a correlation between carbon emissions and income (Zafeiriou et al., 2018). As income increases, so do emissions, for instance, by fuel consumption such as gasoline or diesel. Additional regulations, such as the circular economy package adopted by the European Union, promote the transition of the agricultural industry to sustainability. Partnerships and collaborations, such as Siemens Energy AG and Air Liquide (Siemens Energy AG 2021), H2Giga (Bundesministerium für Bildung und Forschung 2021), and government-to-government (IRENA, 2022), are established to meet this challenge.

Ecosystem theories in a business context began with Moore's predators and prey (1993) paper. Since then, the topic has experienced increasing popularity on both the scientific and business sides. To enable the transfer and implementation of the ecosystem theories, managers are finding more and more non-scientific articles. The German term *Umwelt*¹ was extensively characterized by Jakob Johann von Uexkuell (1909). Uexkuell described, based on the research on animals, that the environment around an individual has a decisive influence on the individual (Gruevska, 2019). The term *Umwelt* characterizes the causal relationship of living beings with their environment. The term environment describes rather surroundings focusing spatial natural elements like air and water (Cambridge University Press 2014b). To transfer the green hydrogen to large-scale applications, the relevant community, the green hydrogen ecosystem (GHE) with its actors, and the relevant framework conditions, *Umwelt* with its trends, must be led by leadership into an innovative and creative future (Faix et al., 2020; Mergenthaler & Faix, 2022). A survey and study in Greece revealed that citizens attribute a more important role (leadership) to governments in combating climate change (Zerva et al., 2018). Citizens are more satisfied with the measures taken by non-governmental organizations (42.41%) than by governmental organizations (state 7.73%, local authorities 16.21%). Outright dissatisfaction and dissatisfaction are quite high at 27.8% and 47.2% for the state and 17.4% and 41.5% for local authorities.

GHE and the associated *Umwelt* are critical if green hydrogen is to be productive. The question arises as to what are the characteristics of an ecosystem and its *Umwelt* to lead green hydrogen to large-scale applications. The focus of this study is on the ecosystem.

Literature Review for Ecosystems Theory

First, the term *ecosystem* must be placed in the context of considering a network of organizations and people. Ecosystem can be described as "...all the living things in an area and the way they affect each other and the environment" (Cambridge University Press 2014a). The transfer from biological living things to social and economic consideration was started by Moore (1993) and others. Since then, ecosystem theories have been a steadily growing topic of science. The abstract platform Web of Science contains 39 articles published around business, economics, and ecosystems ("ecosystem*" AND "business*" AND "innovat*") up to 2015 (Scaringella & Radziwon, 2018). In 2015 and 2016, 47 newly published articles were added. In their theoretical systematic literature review paper, Scaringella and Radziwon (2018) included 393 references around the topic of ecosystems. Selected papers that were considered for this paper are listed below. The descriptions do not claim to be complete. Assorted topics of importance for this paper were extracted.

¹ According to Uexkuell, "The world that surrounds us is the objective reality with which we alone have to deal when we do objective natural research" (translated) (Uexkuell 1909, p. 248).

Moore (1993) described the impact of a business ecosystem on business success using four stages of evolution: birth, expansion, leadership, self-renewal. Specific examples, such as IBM, show that the ecosystem is critical to growth on the one hand, but also the factor in a company's decline within an industry on the other hand. Co-evolution enables ecosystem actors to grow together. A place in the ecosystem could be secured in some cases through patents. A main factor in being an active actor within an ecosystem is continuous innovation.

According to Adner (2010), the risk of innovation-making (the transition to large-scale applications) should be considered systematically and holistically (taking into account the entire ecosystem and its innovations). The timing of required innovations within an ecosystem of different actors is critical as it influences realistic expectations, resource allocation, and, ultimately, the strategy at all. False expectations can demolish value just as quickly as poor execution. In terms of strategy, actors must make the decision whether to take an active or passive role (Adner, 2006).

Walrave et al. (2018) put the focus on the correlation between value proposition and socio-technical² environment for innovation ecosystems. The ecosystem value proposition is created when internal alignment leads to a contribution of the individual actor value proposition to the overall ecosystem value proposition. The external viability of an innovation ecosystem further relies on the iterative adaptation of the ecosystem value proposition and the ecosystem model to the socio-technical environment. The strategic niche management shapes the socio-technical niche level which provides an increased external viability.

According to Scaringella and Radziwon (2018), there are basically the following ecosystem archetypes: knowledge-, innovation-, business, and entrepreneurial ecosystems. The authors also identified seven relevant streams of the territorial approach: "...(1) industrial districts, (2) Marshallian districts, (3) innovative milieus, (4) regional innovation systems, (5) new industrial spaces, (6) localized learning, and (7) regional clusters" (Scaringella & Radziwon, 2018, p. 65). The framework developed by Scaringella and Radziwon considers all elements by identifying the streams. They open the remaining question of what could be a trigger point to transfer from knowledge to an entrepreneurial ecosystem.

The strategy as ecology paper by Iansiti and Levien (2004a) highlighted the similarities between modern business networks and biological ecosystems. There are critical nodes that play the key role of regulating ecosystem health. There are three critical measures of health: productivity, robustness, and niche creation. These can be translated into four strategies for managing the environment. The conclusion, actors can take on three roles: value dominator, physical dominator, and niche player. A company that acts without understanding the effects on its many partner companies or on the ecosystem simply disregards the nature of the interconnected ecosystem and the Umwelt in which it exists.

² "...socio-technical regime: the currently prevailing collection of artifacts, habits and the action-guiding rules about the domain which are upheld by a wide actor network surrounding a vested solution" (Walrave et al. 2018, p. 105; Geels 2004, 2005; Raven 2007).

Valkokari (2015) clarified the interplay between business, innovation, and knowledge ecosystems. The characteristics of all three ecosystem archetypes were outlined. The relationship overlaps and dynamics between all three were discussed. For further research, it is noted that the temporal dimension and changes in governance and roles of different actors in different ecosystems need to be further explored.

Xu et al. (2018) used a bibliometric study to show the connection between science, technology, and business ecosystems. The study focused on the integrated value chain and interactive network using 3D printing in China as an example case. For the value chain in the domain of Chinese 3D printing, it considers the segments of materials, design, equipment manufacturing, and service.

Russell and Smorodinskaya (2018) compared innovation ecosystems to systems and addressed the similarities with complexity science. The triple helix, as the “highest” form of ecosystems, should be targeted based on today’s economic patterns. The identified actor groups are from “...institutionally different sectors, representing business sector, knowledge generating sector (universities, research institutes, other R&D centers) and public sector (government bodies or agencies)” (Russell & Smorodinskaya, 2018, p. 117).

Scientific consideration of system and ecosystem theories seem to have limited application to hydrogen. One of the examples uncovered is the analysis and interpretation of critical hydrogen actors in Denmark by Andreassen and Sovacool (2014). However, systems and ecosystem theories are only touched marginally in this paper. The described growth of green hydrogen requires a scientific view of the green hydrogen ecosystem to systematically enable technological and entrepreneurial developments.

Methodology for Theory Sketch and Expert Interviews

For the present paper, we used an explorative, qualitative study design, because we did not find an application of ecosystem theories specifically on the hydrogen sector in the scientific literature. To define the expression for the theory sketch, a literature review for ecosystems was conducted to identify relevant scientific literature. We focused on joint value creation, emergence, and scientifically defined ecosystem archetypes, as these are initially required to determine the framework for describing the object. Based on the literature review, the expression and theory sketch, a semi-standardized interview was conducted with 22 experts. The insights gained from the expert interviews provide quantitative and qualitative descriptions of human experiences in a holistic way (Mey & Mruck, 2010). The discourse resulting from the research work can lead to an approximation of the actor group-specific perception with the ultimate goal of describing this intersubjectively (Leeming, 2014).

Methodology Theory Sketch

For an exploratory qualitative discussion, it is helpful to illustrate and visualize a theory sketch, as is common in foresight science (Gracht & Kisgen, 2022). The

design of a theory sketch is not similar with designing a theory (Breuer, 2021). The theory sketch is an intermediate step for the creation of theoretical provisional (Glaser et al., 2008). Expressions are helpful to structure guided interviews (Mayring, 2015). They will be the base for the theory sketch too. The expressions and the theory sketch do not claim to be exhaustive. Rather, it is used as the starting point for conducting the expert interviews. The expert interviews aim to verify and validate the theory sketch's assumptions.

Expression: Joint Value Creation of the GHE is Scaling of Green Hydrogen

First, the GHE as an object needs to be described to visualize the theory sketch. The value proposition is a pledge to create value that is delivered to a customer (Lewrick, 2021). The importance of the joint value propositions applies for the GHE too. Despite a promise of a value, it was decided to focus on the joint value creation, which puts the value rather as fact instead of a promise (Chesbrough et al., 2018). According to Adner (2010), the scaling of innovation is a crucial phase for risk-making and the placing of the individual actors. The numbers provided in the hydrogen sections indicate that scaling is needed to achieve the targeted cost reduction for green hydrogen. To do so, surely risk needs be taken. Taking this both together, the scaling of green hydrogen seems to be the focus of the joint value creation.

Expression: Hydrogen and Therewith the GHE are in a Starting Transitions Phase from Gray³ to Green Hydrogen

Having the joint value creation identified, the emergence for GHE would provide more details around the drivers. Walrave et al. (2018) argued that the success of an ecosystem hinges on internal coordination and the external viability of the ecosystem provided by the socio-technical regime. This will be done by iterative manipulation of the ecosystem value proposition and the ecosystem model as object. In this paper, the term Umwelt (as described in the introduction) is used instead of the term socio-technical environment because it limits the focus to the interaction between people, technology, and organizations. Based on the leadership definition, a holistic view of the relevant Umwelt trends is required, independent of the human-technology-organization interaction. As the study from Greece on satisfaction with climate change measures shows, citizens as part of the environment have their subjective impressions (Zerva et al., 2018). These could exert pressure on the actors within the GHE. The actors within an ecosystem are a part of a joint value creation which is based on a joint value proposition. Since there is an already existing total hydrogen demand, 90 million tons in 2020, mainly from fossil fuels (IEA—International Energy Agency 2021), on the one hand, but on the other hand, the political objective to decarbonize, it can be argued that GHE is in a transition from gray to green hydrogen.

³ Gray hydrogen is produced from natural gas by steam reforming with complete GHG emissions (Gribova & Giese 2021).

Expression: Depending on the Business Segments Components, Digitalization, Service, the Nature of the GHE can be Described with Different Ecosystem Archetypes Such as Knowledge, Innovation and Business

To further describe the GHE, it should be aligned with existing ecosystem archetypes in the literature. Scaringella and Radziwon (2018) showed that the business ecosystems described by Moore ((1993), (1997), (2006)) and Iansiti and Levinen (2004b) were further explored into the three ecosystems of knowledge, innovation, and entrepreneurship. Valkokari (2015) grouped the three ecosystems of business, innovation, and knowledge at the same hierarchical level. According to Cobben et al. (2022), there is a limited focus on entrepreneurial ecosystem type even though the publication have increased since 2015. It was decided to use the terms business, innovation, and knowledge ecosystems for further study of the GHE due to their frequent use in scientific work on ecosystems. The term business ecosystem could be considered a proxy for this study's entrepreneur ecosystem. Both ecosystem archetypes have the common baseline of value creation for customers (end user) in common (Link & Sarala, 2019; Valkokari, 2015). Xu et al. (2018) looked at the value chain of 3D printing in China in the segments materials, design, equipment manufacturing, and service. For hybrid products⁴ such as hydrogen production, the requirements engineering needs cover hardware, software, and service elements (Berkovich et al., 2009). Considering that the GHE will not be a homogenous ecosystem “block” over the entire value chain, the three ecosystem archetypes were combined with the value chain elements components, e.g., the electrolyzer (hardware), digitalization (software), and service (operation and maintenance).

Expression: GHE Participants are Segmented into Four Main Actor Groups Governments and Authorities, Science and Research, Hydrogen Market, Equipment, and Service Providers

For the intended expert interviews, a homogenous example group should be targeted. Therefore, it is required to identify the individual actor groups within the ecosystem. According to Russel and Smorodinskaya (2018), the triple helix ecosystem include the representing business sector, knowledge-generating sector, and public sector. At least three groups of actors should be considered. Since green hydrogen needs to be scaled up on the equipment side to achieve economies of scale (CAPEX reduction) and the cost of hydrogen production needs to be reduced by cheap renewable energy (OPEX reduction), it seems reasonable to split the business sector into equipment and service providers as well the hydrogen market (Hydrogen Council and McKinsey & Company 2021). Hydrogen market was initially named prosumer⁵ (Markgraf, 2022). That turned out to be a not-so-common shared term during the interview process. The knowledge-creating sector is described in this study as science and research. The terms government and authorities cover the public sector.

⁴ Hybrid products combine the value creation of physical hardware with service (Leimeister & Glauner, 2008).

⁵ Person or entity who is both consumer and producer at the same time (translated) (Markgraf 2022).

Based on these expressions, the GHE sketch (Fig. 1) was created to serve as a foundation for further research. The theory sketch has the pre-defined joint value creation scaling green hydrogen. There are three segmentations: components, digitalization, and service. It considers four main actor groups, which consist of a collection of diverse actors.

Methodology Expert Interviews

For analyzing the expert interviews, the methodology of qualitative content analysis according to Mayring (2015) was chosen. The selected guiding question interviews are among the semi-standardized interviews. The formulated expressions let to ten direct and one optional guiding question (Appendix 1 – Questionnaire for interview). The categories for the guiding questions are deductive or inductive in nature, depending on the material available. The pre-defined green hydrogen ecosystem (GHE) theory sketch (Fig. 1) was used to guide the interview and provide a mutual understanding. The information was split into several slides to focus the interview on the relevant points. Coding rules were defined based on Mayring's (2015) descriptions with expressions, questions, rule description, anchor examples for the codes, evaluation, objective, findings of both evaluators, and quality criteria testing. After the development of the guided interview, a pre-test was conducted on November 26, 2021 to check the questions, formal procedures, and technical recordings. No major adjustments had to be made. The interviews for the 10+1 questions were conducted in the period from July 12, 2021 to February 2, 2022 with approximately 20 min each. The interviews were virtually done and recorded via Teams (Microsoft). Respondents were informed about the recordings and anonymity was ensured. One respondent did not consent to the recording. In this case, notes were taken by hand. A compiled pre-read with background, research focus, target of the interview, benefit for the interviewees, next steps after the interview, an example for ecosystems, description of the ecosystem's archetypes, and examples of roles and key activities within an ecosystem were send with the invitation.

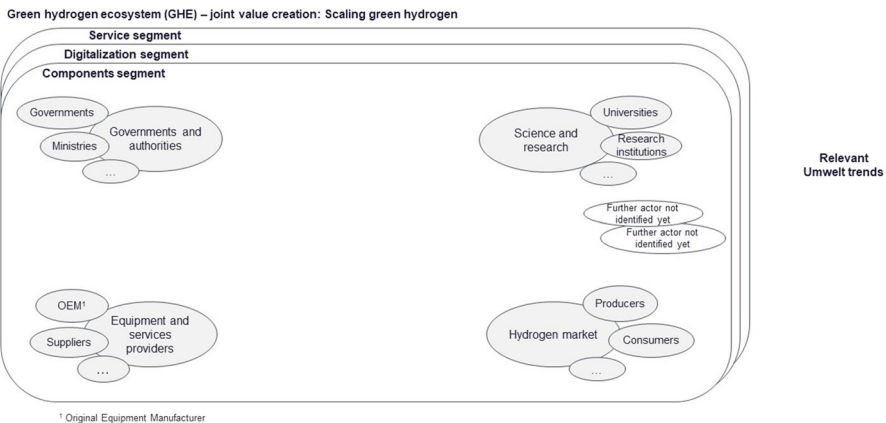


Fig. 1 Green hydrogen ecosystem theory sketch

There is a wide discussion about the right sample size for qualitative research. The number mentioned in the literature ranges from 15 (Clayton, 1997) to 100 (Warth et al., 2013). A compromise between ambition and feasibility had to be found. Feasibility is limited by the time needed to approach the experts, conduct the interview, and analyze it, as well as the availability and consent of the experts. The sample size of 20 seems to be an appropriate balance. Five interviews for each pre-defined actor group. The interviewee must represent at least one of the four actor groups shown in the GHE theory sketch: governments and authorities, science and research, hydrogen market, and equipment and service providers (refer to appendix 2). In addition, the individuals are demonstrably involved in activities related to hydrogen. Sociodemographic factors such as age and gender do not play a role. The interviewees were retrieved from the professional background of the authors or from colleagues. The targeted persons were contacted via email, if available, or via direct messaging on the LinkedIn platform. Finally, 22 interviews were conducted due to delays between interview requests and commitments to participate in the interview, more interviewees have been accepted than targeted. The actor group governments and authorities were represented with seven participations, the others with five. Although this led to an imbalance in the data, we retained all data because each data package contained meaningful information due to the different professional backgrounds and expertise in the green hydrogen ecosystem. In the case of a relevant bias effect due to this partly unbalanced design, the authors draw attention to the section findings and conclusions. The recordings were manually transcribed via Amberscript (© Amberscript Global B.V.). The analysis of qualitative data was performed using MAXQDA Plus software (© VERBI Software). For guiding questions with a deductive approach, the categories were inserted in advance and the respective text passages were marked accordingly. The guiding questions followed an inductive approach; the text passages were marked first, and the categories were formed after the 22 interviews were completed. Coding of the transcripts was performed by two people independently using the coding rules. The results of both were documented in the coding rules and discussed in several meetings. Discrepancies such as overlooking statements or misinterpretations between the two evaluators were noted, discussed, and in all cases settled on a value.

We aimed to maximize the objectivity of the analysis by employing a pre-test and by conducting two independent evaluations of the qualitative data. Nevertheless, we cannot fully objectify such an analysis due to the following factors. We are aware of individual perceptions of the respondents. Thus, the Umwelt influences may play a role here. For example, SARS-CoV 19 influences society as a whole and thus also determines the respondent's perception. The specific implications on the German Energiewende⁶ and the green hydrogen ecosystem by SARS-CoV 19 and its consequences are touched by reports from diverse analysts, e.g., JPMorgan Chase and Co. (Jones et al., 2021), Energiemarkt (Vahlenkamp et al., 2020). Of course, the location of the respondents also has an influence, with one exception, the respondents are employed in Germany, even if they work internationally. Finally, both the survey and the evaluation are influenced by the

⁶ Since Germany is one of the key pioneers of the global energy transition movement, the German term *Energiewende* is widely known (Agora Energiewende 2018).

evaluators. Taking these potential biases into account, we are quite sure that the study can draw a picture of a green hydrogen ecosystem in a holistic way.

Results and Discussion

To lead the transfer of green hydrogen to large-scale application, the ecosystem with its actors and the corresponding environment with its trends need to be explored. This study aims to provide the framework for a description of an ecosystem and its Umwelt for green hydrogen. The categories joint value creation, emergence, and ecosystem archetypes are the characteristics of the framework. They describe the general integration into the scientific ecosystem research.

Joint Value Creation

Results

The first expression, joint value creation, is discussed along with two interview questions. The objective is to identify whether the pre-defined joint value creation applies and different perspectives of the four pre-defined actor groups are considered. The first question follows a deductive approach. The pre-defined joint value creation scaling green hydrogen could be answered by the categories fully agreed, partially agreed, and not agreed. Partially agreed or disagreed triggers the second question, which follows an inductive approach. What is the joint value creation for the green hydrogen ecosystem (GHE)?

Figure 2 shows that the majority agreed or partially agreed with the pre-defined joint value creation. There is a tendency for partial to holistic consent. The distribution between the actor groups is not decisive.

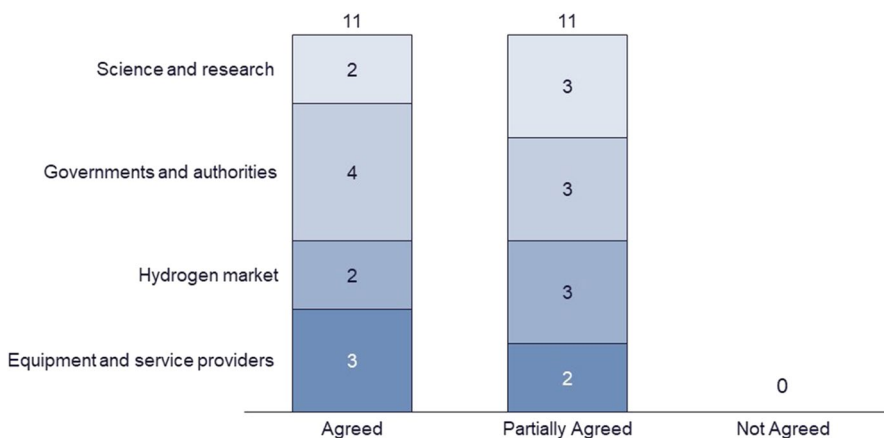


Fig. 2 GHE joint value creation

Some experts provided additional alternatives even agreed to the pre-defined joint value creation. They named 21 alternative joint value creations on the second (optional) questions. Multiple answers from individual respondents were possible. Three main categories could be formed. Below are three randomly selected statements for each category.

Delivery of Hydrogen in the Appropriate Quantity, with the Corresponding Price, at the Desired Location, and at the Right Time (11 Mentions)

- #09: “So it’s a single objective from the perspective of public service, uh public transport, but basically it needs this basis of large-volume, CO₂-free, but cost-effective and-and, ummhh, yes stable supply of-of hydrogen”
- #13: “So in Australia or Saudi Arabia, you don’t have to ask whether you want to scale anything there. That’s already done there. But the question is that /. There are players in the ecosystem who are not yet aware of this; for example, the customers. So for large quantities of hydrogen from overseas, you can now use the port of Rotterdam as a landing point. And this player is also safe. Yes, wonderful, it is fully established, it is already doing so, it also has the scaling. But how it goes on from there is still wide open for me. And there again is the question /. The problem is not scaling the production of hydrogen, but scaling the infrastructure: how does it get to a customer”
- #03: “Because scaling is actually a means to an end. The goal of the off-takers is to get hydrogen, needed quantity, in the needed quantity and at ’n most favorable price. And there are off-takers who, of course, need large quantities. There are off-takers, example industry or mobility applications, which in the first step don’t necessarily need large, ummhh, economies of scale, so no large quantities, but economies of scale in the sense of cheap credits, cheap means of production to buy, ne, ummhh, in the end, uh, the goal of the, ummhh, ecosystem is, I think, to get green hydrogen at the right time at the right place at the best possible price, so in any case competitively, so that the whole value chain can also function economically.”

Achieve Decarbonization Targets (Seven Mentions)

- #11: “And that is the driver. We want to de-fossilize our, our society. We have several ways to do that. One of them is hydrogen and the other one is, as you know, direct electrification.”
- #01: “So, I would’/. Exactly. I would add a second category to “earning money.” Avoid CO₂.”
- #09: “Ummhh, ah, let’s say the objective, ummhh, now with us and so a hydrogen as an energy carrier to use, ne would be that we offer yes CO₂ free traffic.”

Enable Small Pilot Application for Risk Minimization (Three Mentions)

- #21: “Um, let’s say that we have made the experience, that we have approached this- this topic of hydrogen and the topic of value creation in “...” rather um, let’s say, in very small projects in very small steps. And that also these projects, um, at least it was like that in the past, um, rather had a chance of realization.”

- #07: “Here, too, we have now submitted at least a sketch, i.e., a small research project, so that we can show that this also works technically.”
- #06: “I think the collaborative approach to the topic is not yet quite there because of the no-novelty of the topic, because I think the discovery phase of the different actors in the individual ecosystem is not yet fully developed, both on the intra-organizational level, i.e. on the organization’s own platform and level.”

Discussion

The expert interviews revealed for the pre-defined joint value creation that there is a tendency of partial to holistic agreement. There is mainly a homogeneous distribution between actor groups. That indicates an overall good status on the ecosystem internal alignment between the pre-defined actor groups. The tendency of partial to holistic agreement is probably based on scaling to an end. Considering the alternatives provided by the interviewees, the joint value creation should cover the following aspects.

- Delivery of hydrogen in the appropriate quantity, with the corresponding price, at the desired location, and at the right time
- Achieving the decarbonization targets
- Enable small pilot application for risk minimization

The first two points require scaling otherwise green hydrogen will remain as niche product what will not achieve a respective volume with a corresponding price (economies of scale) at the needed place at the right time and will only contribute limited to the worldwide decarbonization targets. Enabling small pilot applications to mitigate risk can be seen as a measure to enable overall joint value creation since it is the step before scaling. Since there is agreement among the ecosystem actors, it can be assumed that they will do their “best” to achieve this joint value creation.

Emergence of the GHE

Results

The second expression, emergence, deals with the trigger points for the transition from gray to green, the timing, and the current phase the green hydrogen ecosystem (GHE) is currently in. The aim is the identification of the event that initialized the birth of the GHE, the time of birth, and the current maturity of the GHE in relation to the phases birth (beginning of transition), expansion (advanced transition), leadership, and self-renewal (combined in completed transition) defined by Moor (1993). The first and second interview questions to identify the trigger points from gray to green hydrogen and their timing are an inductive approach. The third, rate the degree of the transition from gray to green, is deductive with the following three categories: start—transition has only just begun; advanced—transition is mature; completed—transition is finished.

Multiple answers were possible for the trigger points. The key terms were identified, which were grouped into categories, as shown in Table 1. The primary event that triggers the emergence of GHE (23 mentions) is the political objectives, e.g., the Paris agreement to limit greenhouse gas emissions. The second is the will to decarbonize (12 mentions) and the third is the price competitiveness of green hydrogen versus fossil alternatives (nine mentions). Certainly, there is overlap in the key terms, as all topics are interrelated.

Figure 3 shows that here is an accumulation for the timing of the trigger point in 2018, 2019, and both years (in total nine mentions). Three times the trigger point was mentioned in the future and once as always existing or without a specific time.

Table 1 Key trigger points for emergence of GHE

Key terms	Mentions	Categories
Willingness to pay green offset Cheap renewable electricity in large scale High prices for fossil raw commodities	5	Price competitiveness of green hydrogen versus fossil alternatives
Will of companies to decarbonize (inherent goal) Climate neutrality by international trading partners Self-selected environmental social governance investment criteria Fridays for Future International consensus on decarbonization (not completed yet)	12	Willingness to decarbonize
Copernicus project financed by German government Renewable energy directive (RED), European government Local target from the region, commissioned by cities International carbon markets Paris Agreement, COP21, 2015 A hydrogen roadmap for a climate-neutral Europe 2020 National hydrogen Strategy Germany 2019 “Energiewende” in Germany Geostrategic consideration Penalties for CO ₂ emissions e.g. CO ₂ price Subsidies for green hydrogen	23	Political objectives

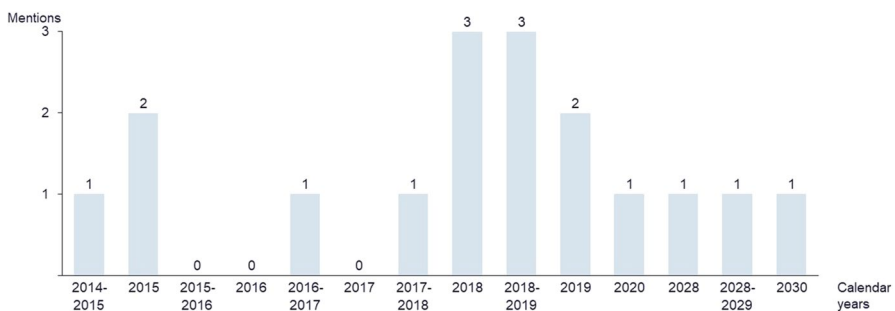


Fig. 3 Timing (years) for trigger point of the GHE

All experts explained that the transition from gray to green hydrogen is at the beginning, sometimes reinforced with the addition of absolute beginnings. The distribution between the actor groups is not relevant.

Discussion

Having the joint value creation identified, the Umwelt must be studied. Beside the inherent decarbonization goals of society, e.g., Fridays for Future Movement, and companies and the price competitiveness of green hydrogen versus fossil alternatives, and the political objectives, e.g., Paris agreement, were mentioned as an initial trigger point for the green hydrogen ecosystem (GHE). It reflects the process of alignment between the political agenda and younger society's expectations for the future, including but not limited to climate change, democratization and social fairness (Marquardt, 2020). The identified joint value creation is in line with the demand of the Umwelt since the decarbonization is mentioned for both. The agreed policy targets like the Paris agreement are necessary framework to shape the transition towards decarbonization. Providing green hydrogen in the appropriate quantity, with the corresponding price, at the desired location, and at the right time is the resulting joint value creation of the GHE. The price competitiveness of green hydrogen versus fossil alternatives can be considered as consequences of implementing the joint value creation—scaling will drive costs down. If the GHE and its actors can deliver the described joint value creation, their external viability should be ensured by the demand of the Umwelt to decarbonize. On an iterative basis, joint value creation must be adapted to the requirements of the Umwelt over time (Walrave et al., 2018). Further research could be conducted on additional relevant Umwelt trends impacting on the GHE and vice versa.

Looking at the timing, after the release of the political objectives in Paris in 2015, it took another 3 to 4 years (2018/2019) that more precise hydrogen roadmaps, e.g., Nationale Wasserstoffstrategie⁷ of Germany (BMW, 2020) or the European Renewable Energy Directive I and II (European Union 2018), were released. End of 2021, beginning 2022 the transition towards green hydrogen is in a very early stage. This offset is interesting in that it allows conclusions to be drawn about the speed of birth of new ecosystems to be initiated. Further, the iterative adaption of the joint value creation to the Umwelt seems to have a rather long-term cycle. This could be subject to further research.

Moore (1993) outlined that a business ecosystem in the starting phase has the cooperative challenge to collaborate with customers and distributors to launch the new value creation around a basic innovation. That seems to be at the final stage, since there is a common understanding about the joint value creation respectively about the value proposition. There is a common agreement that the realization of increasing amounts on green hydrogen are still at a very early stage. That would refer to the expansion phase of a business ecosystem that must provide new offers

⁷ National hydrogen strategy of Germany (translated).

to a more brought market. Thus, the scaling of green hydrogen seems to be at the center for the current activities. Since Moore considered business ecosystem mainly, the question which needs to be discussed is, whether the GHE is only allocated to the archetype business ecosystem, or does it combines elements of innovation and knowledge ecosystems as well?

Ecosystem Archetypes

Results

Experts were interviewed on the use of the three ecosystem archetypes (knowledge, innovation, and business) and the holistic mapping of green hydrogen ecosystem (GHE). Further, agreement and evaluation were requested to map the pre-defined segments (components, digitization, and service) with the ecosystem archetypes, the identification of an alternative segmentation, and the trigger point the GHE needs to take to make a developmental leap between the archetypes. Using a deductive approach, respondents were asked whether they fully agree, partially agree, or disagree with the application of the business, innovation, and knowledge ecosystem archetypes to the GHE. Eighteen agreed, four partially agreed, and none disagreed with this approach. Figure 4 shows that the distribution between the actor groups is not decisive.

For the holistic classification of the GHE into archetypes, respondents were interviewed on a deductive basis. There is a dominance for all three ecosystems at the same time and the transition between innovation ecosystem and business ecosystem archetype (both eight mentions). Pure innovation ecosystem was mentioned four times und business ecosystems two times. The application of the pre-defined segments for components, digitalization, and service was answered with 13 agreed, seven not agreed, and two abstentions (Fig. 5). The main contribution (four

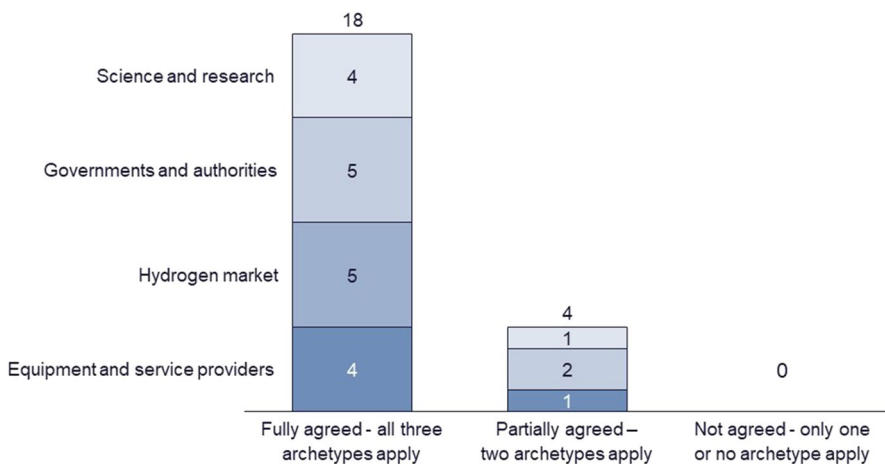


Fig. 4 Application of different ecosystem archetypes

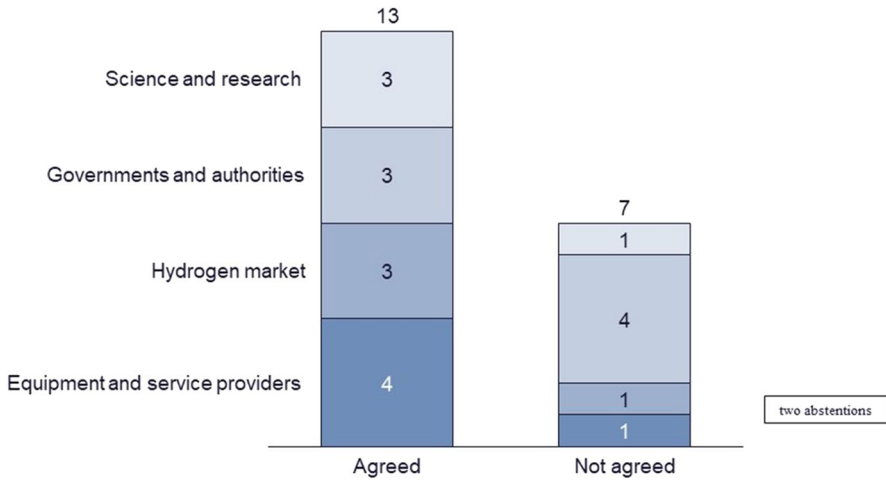


Fig. 5 Agreement with the pre-defined segmentation

Table 2 Ecosystem dominance for segments components, digitalization, and service

Segments	Ecosystem Dominance for Segments						Sum	Abstentions or no clear allocation
	Knowledge	Transition Knowledge-Innovation	Innovation	Transition Innovation-Business	Business	All Three		
Components	0	1	1	5	3	3	13	9
Digitalization	0	3	4	3	2	2	14	8
Service	1	1	3	4	0	2	11	11

mentions) to not agreed is made by governments and authorities. As there are two additional respondents from this actor group, a bias of this actor group should be considered.

The assignment of the different archetypes to the pre-defined segments is based on a deductive approach. Table 2 shows that the ecosystem for components is in transition from innovation to business ecosystem with a tendency toward business. Digitalization has its focus in innovation and service in the transition from innovation to business with a tendency toward innovation. For the highest accumulations of the assignment, the statements out of the interviews are outlined in the following (statements in German translated into English by the author).

Components: Innovation in Transition to Business Ecosystem (Five Mentions)

- #09: ...”So I would almost include this in this business, whereby the design is ultimately accompanied by scientific research, because where do I have the customers, how much and so on and so forth, that already fits. The other was digitalization and?”

- Interviewer: “Digitization and service. So very briefly, ummhh, so the-the hardware, or the/ the electrolyzer itself, so somewhere in business, but also maybe a bit of innovation I heard out.”
- #09: “Yes, exactly.”
- #06: “Of course, hardware is, ne, depending on where you / where we now start in the discussion stage, ne, also from the chronology, ummhh, there are certainly arguments both for “Business Ecosystems” and for innovation, ummhh, so “Innovation Ecosystems.” Ummhh, just off the top of my head, no, we would have to really take a look at exactly which hardware and in which context it will be used.”
- #11: “Yes, that’s right, that’s exactly right. You can say that, I would also say that. So if you open up these three lines, i.e. with digitization and also services, I would have said that digitization and service are behind in this development. So, I would have the feeling that we are still more in the area of knowledge, so to speak, with both. Eh, stop stop, eh stop. I would say differently for services. We make times for the, for the digitization, there I would say, there one hangs still a little bit more in this, in this Knowledge, in this, or there the emphasis is more in the knowledge area and perhaps at the border to the innovation and to the Business. Now I know so close to your example that you say you also want to make business out of it. But I think you’re probably a bit further along on the hardware track.”
- #13: “If you look at the three sides, then I would say that all three are mainly part of the innovation ecosystem,—with the transition to business. Because, as I said, if you imagine that you have a 100-megawatt electrolyzer that you’ve sold “...” you’re not doing any more research, and there- there’s everything/there’s all three parts /. I think the three-part division you have chosen makes a lot of sense, but you have to master all three, otherwise you won’t be able to sell such an electrolyzer.”
- #02: “I think, okay, hardware depend- for PEM, between innovation and business, right?”

Digitalization: Innovation Ecosystem (Four Mentions)

- #06: “Well then, I would see digitization relatively clearly in the innovation ecosystem”
- #01: “I would put hardware in the innovation ecosystem. Digitization, too. And I would assign service to the business ecosystem.”
- #19: “Digitization? Yes, that’s a good question. Yes, I think it also depends very-very strongly on that. Ummhh, but in the first area, I’d still focus on /. Yes, I believe that there is still a great deal possible and a great deal feasible, and we still must do a great deal, because I would first put that into innovation.”
- #07: “Ummhh, I have a bit of a hard time with the knowledge ecosystem., I would have seen certain topics that might be in the area of ummhh trade with hydrogen, uh, certain, maybe transport possibilities or also the topic of digitalization, I would have rather seen them there and many other things more in this area of innovation.”

Service: Innovation in Transition to Business Ecosystem (Four Mentions)

- #09: “Yes, well, I would also say that the service is, for the most part in our area, probably relatively simple, because ... of course we have to adapt. But I don’t think there’s much that’s new or must be done very differently than in the gas business now. So, this now refers to purely transport. Service for electrolyzers, I don’t know. I can imagine that this is also still quite fresh and new, that we may also be able to apply all these subsystems.”
- #11: “And on the subject of service, I would have said that the subject of service is probably something that, ummhh, well, my gut feeling is that it’s probably in the ... or with a very large focus in the area of business, but is also underdeveloped there, because, yes, there are not yet the facilities, so you know, that’s ... And I have the feeling that the hydrogen sector is not yet developed at all, because there are no plants, so to speak, that ... So, this will only develop here the more plants there are. So, I have the feeling that this is also totally underdeveloped, and if it is, then I would see the focus in the business ecosystem.”
- #13: “If you look at the three sides, then I would say that all three are mainly part of the innovation ecosystem,—with the transition to business. Because, as I said, if you imagine that you have a 100-megawatt electrolyzer that you’ve sold “...” you’re not doing any more research, and there- there’s everything/there’s all three parts /. I think the three-part division you have chosen makes a lot of sense, but you have to master all three, otherwise you won’t be able to sell such an electrolyzer.”
- #16: “...then we start once with the service. I think that’s where you just... It’s a bit difficult, because you can only really offer service if you have a plant for which you do service, and you also need the corresponding knowledge about the plant in order to offer the service in a meaningful way. I don’t think you really need to do much research on that. But I would classify that between innovation and business, because they also come from other/ So I think it won’t be so massively different between what we do for other plants.”

The inductive evaluation for an alternative segmentation in comparison with components, digitization and service are as follows. Multiple responses were possible in the surveys. The number of mentions is not decisive since the exploratory investigation to identify alternative segmentations is in the foreground. Basically, the two different groups value chain independent clustering and actor groups within the value chain are named for an alternative segmentation. In addition to hydrogen consumers as part of the value chain, power to X (PtX)⁸ consumers are also mentioned. Since green hydrogen is considered as the basis here, the GHE should include consideration of the entire value chain, including PtX.

⁸ PtX is a process for converting renewable electricity into hydrogen by electrolysis of water. The hydrogen can be used directly or further processed into other energy sources such as heating, cooling, liquid fuels or chemicals (Wulf et al., 2020).

Value chain independent clustering:

- Political pull, technological push, and business model push
- Central and decentral applications
- Size of productions

Actor groups within the value chain:

- Energy supply
- Equipment producers
- Hydrogen production
- Infrastructure for distribution, e.g., storage, distribution system operator, gas system operator
- Hydrogen consumers, incl. different PtX applications

The final inductive question about measures the GHE needs to take to make a developmental leap between archetypes received 43 mentions (Tables 3 and 4). Multiple answers were allowed. (Statements in German translated into English by the author).

Discussion

The ecosystem archetypes business, innovation, and knowledge are taken as base for an allocation of green hydrogen ecosystem (GHE). Most of the interviewees agreed to take those. There is no single ecosystem archetype that is currently active. All three are active with different dominance after the introduction. Green hydrogen in particular shows that when there is a strong political push by objectives such as the Paris agreement, all three ecosystem archetypes take effect in parallel and in a pronounced manner. For the commercial attractive operation, there are missing single technologies along the value chain, which are still in knowledge ecosystem, e.g., anion exchange membrane for hydrogen production, compressors with hydrogen filling stations in the transport sector, or e-kerosene in flight operations. This parallel shaping is a challenge for all actors, as the business is highly risky if, the technologies along the value chain are not fully developed and tested especially for large scale. The business ecosystem aims to drive large-scale application under market conditions, while the knowledge ecosystem works to develop technological fundamentals—the knowledge and the information as foundation for value creation in a knowledge economy (Del Giudice et al., 2017). At the same time, business models are already being developed in the innovation ecosystem. This observation is in line with Adner's (2006) observation, that the innovation ecosystems pose a new series of risks. In other words, new complexities will emerge that can frustrate the best attempts. Different ecosystem characteristics are needed for different technologies along the value chain. Even if all three ecosystem archetypes apply, the innovation and business ecosystem seem to prevail. That can be seen in line with the almost complied birth phase of the GHE—emergence of the GHE.

Table 3 Leap from knowledge to innovation ecosystem

Categories	Mentions	Anchor examples (randomly selected)
Technical and economical basics are known for the transfer	5	#03: "Between knowledge and innovation. Ummhh, probably it is crucial, in the innovation ecosystem, one already has an idea, how a product or a solution, ummhh, could look like and is already working very intensively to bring that towards economic viability, so one has already, ummhh, defined goals for this innovation, development goals and, uh, on the topic of knowledge, one is probably still closer to basic research and has not yet calculated a business case probably for the application. So it's probably, if I were to talk now about the new technologies in the hydrogen field, uh, to talk about, I was uh AEM in the new technology, we are probably still between knowledge and innovation ecosystem and at- at PEM between innovation and business ecosystem, and at Alkaline rather in the business ecosystem."
Networks among research and development institutions	3	#16: "... and networking with the research community as well, so that we can find out in good time what developments there may be that could accelerate the technology paths."
Industrial demonstration in market environment with validation	2	#18: "From 'knowledge' to innovation is, I think, simple / that is a demonstration project, I would say. Well, I have a lot of 'knowledge' in that I do research, stand in the lab and so on. I don't think I can inspire a company director with that. There are the innovation leaders, there is always somehow, let's say, a CEO who is very innovation-oriented and also courageous and somehow makes decisions and says: Do something. For most people, what I've experienced is when they see the demonstration, like we did with the 500 KW electrolyzer, then, uh, here in "... down then put something and suddenly people have seen: Hey, that works somehow, that's possible. Then I think we get into the innovation phase. Ummhh, so it speaks for me, if one would look for such a point, that would be demonstration, ummhh, on the basis of a small industrial project. So out of the lab, into the market demonstration. So market is already too exaggerated, I'm already too far. Industrial demonstration."

Table 4 Leap from innovation to business ecosystem

Categories	Mentions	Anchor examples (randomly selected)
Economically self-sustaining in the market environment	14	#03: "... Yes, profitability is also a decisive factor here. So, I think, innovat-, in the innovation ecosystem, there is still a lot of experimentation going on, there is still a lot of, uh, improvement going on. We can hardly give any guarantees to the customers, and we can't supply any competitive products comparable to conventional energy sources. So, the goal is to end up somewhere around two euros per kilogram of hydrogen, i.e. comparable to gray hydrogen, although it has now also become more expensive due to the higher gas prices. But if we can produce hydrogen economically, comparable to gray hydrogen—sustainably economically—and can give the customer corresponding guarantees, performance guarantees and delivery commitments, then I believe we will have grown from an innovation ecosystem into a business ecosystem."
Risk minimization in the business case, e.g., guarantees	8	#02: "I think, to be honest, knowledge to innovation, it comes when- from the academia, goes to companies, right? That- that's where, you know, you have the technologies thing, the R&Ds and academia, et cetera. Suddenly people find out there is a business to do and then it starts moving up the innovation and people start thinking, "How do I mitigate risk?" Right? And mitigate risk is by collaborating. And then when it starts getting more mature and then large companies start drafting that, they put in their frame, which is a business frame, right? A tender, supplier, give me pri- you- you know, very, very quickly, companies that have been used to be very professional will try to move from the innovation to the business ecosystem, right, because they will start talking about suppliers, negotiating guarantees, et cetera, and at that point time, they make the diff- they make the difference between those that they value maturity and those they don't have the maturity because then you suddenly get confronted with professionals."

Table 4 (continued)

Categories	Mentions	Anchor examples (randomly selected)
Political regulations implemented	6	#19: “Yes, I believe that the legal framework conditions are often decisive, that they are also geared towards enabling the term “level playing field,” i.e. also in comparison to conventional or established technologies and areas. That is, I think, quite often the case, but of course also a certain acceptance and knowledge among the stakeholders. So yes, I think funding programs can set something at the beginning, ummhh, or even before that. So from research, uh, from knowledge to innovation, probably research programs and then in innovation pilot projects, so promotion of pilot projects. But then, at the latest, when you make the leap from innovation to business, you need a legal framework. Framework conditions that also, yes, establish or enable a level playing field, as they say. In other words, a level playing field between the technologies, between the approaches.”
Networks established (value chain with all actors fully developed)	5	Interviewer: “What is necessary to get into the business ecosystem?” #13: “to map the entire value chain, which has not been mapped as a whole so far.” #13: “Because the production of an energy carrier only makes sense if you have scaled production, transport and use equally, at the same time on the same scale. And if you don’t do that, then there’s a bottleneck, and the bottleneck is deadly, so that it gets into the business system.”

To describe more precisely which ecosystem archetype applies, segmentation seems generally desirable. The segmentation into components, digitalization and service is limited accepted. Consequently, an allocation of those three segments to the three ecosystem archetypes are unpractical. The experts provided the position to reflect the green hydrogen value chain through the following groups for segmentation: energy supply, equipment producers, hydrogen production, infrastructure for distribution, and hydrogen consumers incl. different power to X (PtX) applications. Furthermore, a non-value chain-based segmentation was mentioned with political pull, technological push and business model push, centralized and decentralized applications, and size of productions. However, a segmentation based on the value chain seems obvious, as it offers the possibility to look at the status of the individual technologies along the value chain in more detail. It is recommended to test the value chain segmentation for practicality. However, the answer given shows that the components are rather in transition from innovation to business ecosystem with a tendency towards business. Digitalization has its peak in innovation. The service is in transition from innovation to business with a tendency to innovation. It seems logical that the transition from knowledge to business components must be pioneered, as they must be developed before digitalization and service can be built upon. As mentioned earlier, this needs to be considered for the individual technologies. Even at the component level, there are technologies that are mature and technologies that are at a very early stage of development. This reflects the three mentions that apply to all three ecosystems simultaneously. The result show that there is a demand to consider the ecosystems and segmentation in a holistic lifecycle view of the joint value creation. Therewith, the GHE increases the number of network nodes (Russell & Smorodinskaya, 2018). Behind the nodes, there are the actor groups. It is recommended to spend further research around the actor groups, objectives, and roles, focusing on leadership structures along the knowledge, innovation, and business ecosystem archetypes.

Xu et al. (2018) suggested that further research should focus on the trigger points for a transition from knowledge to business ecosystem. It seems that between knowledge towards business, the innovation ecosystem needs to path through. The question is, what are the trigger points for the GHE to complete the status of the ecosystems? From the knowledge ecosystem to the innovation ecosystem, the fundamental developments must be completed. Interestingly, the knowledge ecosystem should be responsible for industrial demonstration. For this purpose, networks for research and testing should be established. Once these issues are completed, the innovation ecosystem is called upon to drive technology maturity and commercial projects into economically self-sustaining solutions that eventually survive in a market. This increases the certainty of green hydrogen availability, giving consumers the choice to switch to green alternatives. This requires the establishment of networks for the entire value chain. The implementation of government regulations to mitigate the risk of investment, such as the design of niche markets or feed-in tariffs, is cited as a key trigger point. This results in more security for investments and commercial operations. It shows that user-centered innovation with an agreed communication process is needed for real-world testing (Del Giudice et al., 2013).

The leader within an ecosystem has a special role, since the leader needs to tackle the holistic risk within the ecosystem as well its own, and the investments by a leader are usually larger than those of the non-leader within an ecosystem. The governments and authorities have given the objective of decarbonization through the Paris agreement and additionally published country-specific hydrogen roadmaps. This is in line with the expected dominance of the state in measures to combat climate change (Zerva et al., 2018). What partially is missing, for example, the design of niche markets or feed-in tariffs through legal frameworks. The question arises: what is missing for governments and authorities to lead through appropriate regulation? That remains as further research for the GHE. To sum the trigger points for a transition from knowledge to innovation to business ecosystem up, it is required to shape a stable self-sustaining green hydrogen market with reduced risks for all parties by having bilateral long-term contracts and common agreed and accepted regulation framework provided by governments and authorities around the world (IRENA, 2022).

Conclusion and Outlook

The objective of this paper was to investigate the joint value creation, emergence, and ecosystem archetypes for the green hydrogen ecosystem (GHE). We adopted an exploratory, qualitative study design by using the methods literature review, which led to four expressions and a theory sketch as a starting point for expert interviews. The semi-structured interview guide for the expert interviews provided qualitative and quantitative insights for the research. However, as described, the limitations of the quality criteria of expert interviews must be considered. Therefore, it is recommended to extend the range of subjective experiential reality of the interviewees by interviewing more experts outside of Germany and to implement a panel for continuous assessment of changes in the GHE. Nicotra et al. (2018) proposed in a comprehensive study a framework for the causal relationship between entrepreneurial ecosystem and productive entrepreneurship that could be used as a basis to measure the progress of the GHE in a panel study. This should contribute to a continuously improved understanding of the GHE.

The results of the study revealed a consistent view on the joint value creation which indicates a good common understanding among the various actor groups. As Lewrick (2021) pointed out, the value proposition of the ecosystem, the

foundation of value creation, is comparable to a contract between all actors. A consistent view shows that there is a shared understanding of what is in the contract. The joint value creation is: The objective of the GHE is decarbonization by providing green hydrogen in the appropriate quantity, with the corresponding price, at the desired location, and at the right time. Scaling is seen as an enabler and process of risk-taking in the innovation process, according to Adner (2010), but not as a necessary part of joint value creation. The emergence shows that green hydrogen is at the beginning of the journey to decarbonize the world with sustainable and secure energy supply, consistent with Aurora's report (2021a). The Umwelt needs to be considered as it will impact the joint value creation of the ecosystem, but rather on the long-term cycle, due to its influence on political objectives as outlined by Walrave et al. (2018). The Umwelt reflects the perception of end consumers and the society as such. For example, the agricultural sector, which consumes gasoline and diesel, could benefit from affordable green hydrogen (Zafeiriou et al., 2014, 2018; Zerva et al., 2018). The proper balance between economic-ecological measures must maintain socio-cultural stability. The move from the birth to the expansion phase, which corresponds to the transition from an innovation ecosystem to a business ecosystem, is the logical next step. This will entail a number of changes, such as in governance (Moore, 1993, 1997). For segmentation of the GHE, the entire value chain with energy supply, equipment manufacturers, hydrogen production, infrastructure for distribution, and hydrogen consumers including different power to X (PtX) applications should be considered. This value chain consideration is in line with the study of Xu et al. (2018). An important prerequisite for the continuous development of the GHE is the creation of a self-sustaining market for the purchase of green hydrogen (IRENA, 2022). This would mitigate the risks and accelerate the transition to large-scale applications as outlined by Adner (2006).

After defining the object GHE, as a next step, it is recommended to further study the architecture and characteristics around the pre-defined actor groups and the leadership structure of those as well the temporal dimension and changes in governance and roles of different actors in the various ecosystems. Further, it is required to investigate the processes between the actor groups, the influence of additional Umwelt trends on them, and the long-term cycle of iterative adaption of the joint value creation to the Umwelt. This will lead to a comprehensive picture of the GHE.

Appendix 1 Table 5

Table 5 Questionnaire of interview

Expressions	Categories	Expert interview, guiding questions
The joint value creation of the GHE is scaling of green hydrogen	Deductive approach for pre-defined joint value creation: Fully agreed – scaling of green hydrogen Partially agreed – not only scaling of green hydrogen Not agreed– anything else, but not scaling	1. Do you agree with the joint value creation of scaling green hydrogen? Please select fully agreed, partially agreed, not agreed (2. In case of disagreement, what is the joint value creations?)
Hydrogen and therewith the GHE are in a starting transitions phase from gray to green hydrogen	Inductive approach for identification of trigger point and the timing Deductive approach to the degree of transition: Start of the transition from gray to green Advanced transition from gray to green Completed transitions, almost green	1. What was the trigger point for a transition from gray to green hydrogen? 2. When was this trigger point? How would you rate the degree of transition from gray to green today? (Start of transition, advanced, completed)

Table 5 (continued)

Expressions	Categories	Expert interview, guiding questions
Depending on the business segments components, digitalization, service, the nature of the GHE can be described with different ecosystem archetypes such as knowledge, innovation and business.	<p>Deductive approach for application of diverse archetypes:</p> <ul style="list-style-type: none"> Fully agreed – all three ecosystem archetypes apply Partially agreed – two ecosystem archetypes apply Not agreed – one or none ecosystem archetypes apply <p>Deductive approach for assignment of GHE to ecosystem archetypes:</p> <ul style="list-style-type: none"> Knowledge ecosystem Innovation ecosystem Business ecosystem Transition between ecosystems knowledge to innovation Transition between ecosystems innovation to business All three at the same time <p>Deductive approach for diverse archetypes depending on business layer:</p> <ul style="list-style-type: none"> Agreed Not agreed <p>Deductive approach for selection of archetypes for hardware product, digitalization and service layer</p> <ul style="list-style-type: none"> Components – knowledge, innovation, business, transition, or all three Digitalization – knowledge, innovation, business, transition, or all three Service – knowledge, innovation, business, transition, or all three <p>Inductive approach for identification of an alternative clustering</p> <ul style="list-style-type: none"> Inductive approach for evolution of archetypes 	<p>Do you agree that the three different ecosystem archetypes knowledge, innovation, business apply? Please select fully agreed, partially agreed, not agreed</p> <p>Could you assign the GHE to the ecosystem archetypes? Do you agree with different ecosystem archetypes depending on the business layer like hardware product, digitalization or service? Please select: Agreed, not agreed</p> <p>What ecosystem archetype (knowledge, innovation, business) would you select for components, digitalization and service layer?</p> <p>What could be an alternative clustering?</p> <p>What is required, what is the trigger point for a transition from knowledge to business to innovation ecosystem during an evolution process?</p>

Appendix 2 Table 6

Table 6 Table of interviewees

#	Actor group	Position
01	Equipment and services provider	Country Lead for Government Affairs
02	Equipment and services provider	Executive Vice President for Hydrogen Business
03	Equipment and services provider	Vice President Sales
04	Equipment and services provider	Vice President Strategy
05	Equipment and services provider	Chief Technology Expert
06	Hydrogen market	Head of Commercial and Central Task
07	Hydrogen market	Managing Director at Municipal Utility
08	Hydrogen market	Technical Manager Hydrogen
09	Hydrogen market	Business Unit Management
10	Hydrogen market	Chief Technology Officer
11	Science and research	Professor of Power Engineering
12	Science and research	Professor of Digitalized Energy Systems, Head of Energy R&D Division
13	Science and research	Director of the Research Institute for Chemical Energy Conversion
14	Science and research	Professor for Chemistry
15	Science and research	Retired Director Chemical Engineering and Biotechnology Professor for Climate Neutral Chemicals Production Technologies and Process
16	Governments and authorities	Head of Basic Research and Coordinator at Research Institution
17	Governments and authorities	Politician, Former Parliamentary Group Chairman
18	Governments and authorities	Chairman Association and Federal Commission for Energy Policy of the German Economic Council
19	Governments and authorities	Policy Advisor Senate Department for Economics, Energy
20	Governments and authorities	Director-General, Federal Ministry
21	Governments and authorities	Policy Advisor Senate Economy, Labor, Transport and Digitalization
22	Governments and authorities	Former Member of the Bundestag, Hydrogen Innovation Officer

Author Contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by the first author. The first draft of the manuscript was written by first author and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding Open Access funding enabled and organized by Projekt DEAL.

Data Availability All data generated or analyzed during this study are included in this published article. The audio records of the expert interviews are not publicly available due confidentiality of the interviewed experts.

Declarations

Ethics Approval This research involved human participants. Ethical approval is not applicable for this article. Our institution does not require ethical approval for this case.

Informed Consent Experts interviewed were informed in verbal form about the background of the study and the recording of the interviews. It was agreed not to publish any personal data.

Competing Interests The authors declare no competing interests.

Employments Daniel Schwappach is employed by Siemens Energy during the preparation of the study. Werner G. Faix and Jens Mergenthaler are employed at the School of International Business and Entrepreneurship at Steinbeis University, and Claus-Christian Carbon at the University of Bamberg, Bavaria, Germany.

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