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Hydrogen Economy Development Opportunities by Inter-Organizational Digital Knowledge Networks

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Abstract: Innovative power-to-X (P2X) technologies, as a set of emerging new solutions, could play a crucial role in creating sustainable, carbon-neutral economies, such as the hydrogen economy. These technologies, however, are generally not yet implemented on a commercial scale. This research focuses on how innovative, digital inter-organizational knowledge networks of industry representatives and universities could contribute to the commercial implementation of P2X technologies and increase the pace of sustainable hydrogen-based development. The findings of an extended case study with a hybrid (qualitative–quantitative) methodology and a five-year time horizon, suggest the need for a digital knowledge platform, where universities and industry representatives add and combine their knowledge. In contrast with expectations, however, the empirical results show that academia would, not only be capable of supporting the exploration of new solutions, but foster the exploitation of more mature technologies as well. Similarly, large energy companies could also drive exploratory activities, not only exploitative ones. The findings highlight the possible central role of the “system builder” actor, who integrates exploitative-explorative learning and facilitates the formation of a (digital) innovation ecosystem. By exceeding the dominant techno-economic and environmental aspects, this research contributes to the literature by highlighting the applicability of network-based innovation management theory for hydrogen economy research.

Keywords: hydrogen economy; P2X technologies; knowledge networks; industry-university cooperation; innovation management



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1. Introduction

Immense pressure on societies in developed countries to create carbon-neutral economies requires rapid innovation and technological development as well as knowledge transfer related to renewable energy technologies, energy storage, and smart energy systems [1]. A promising strategic direction for creating carbon-neutral economies is the hydrogen economy, which is “a proposed system where hydrogen is produced and used extensively as the primary energy carrier” [2] (p. 1572). Industry actors and scholars argue that power-to-X (P2X), especially power-to-gas (P2G) (including power-to-hydrogen (P2H) and power-to-methane (P2M)) and power-to-liquid (P2L) technologies are innovative in this area. These technologies can absorb surplus renewable electricity, provide network balancing services to reduce maintenance costs and energy storage solutions to avoid energy loss, integrate energy sectors, reuse carbon dioxide, and consequently facilitate sustainable transitions [3–5]. Innovative P2X technologies, however, are not widely implemented on a commercial scale yet, and research results suggest that change in the energy sector is hampered because of the exploitative, risk-averse routines of large energy companies and the strict institutional background [6,7]. This phenomenon has been supported recently by empirical evidence in the case of P2X technologies as well [8].

Even though the literature has already covered several aspects of P2X technology development and implementation mainly based on quantitative methods (for example, process design, technical performance [9], or even macro-level technical and financial potential [10]), in-depth analysis of the managerial and technology development processes is mostly overlooked. This phenomenon is also visible with regard to broader hydrogen economy research. The latest works focus, for example, on the optimal synergy of photovoltaic panels and hydrogen fuel cells [11], life-cycle assessments of materials in hydrogen technologies [12], comparison of hydrogen and ammonia [13], waste-heat utilization [14], or a review of policy framework [15].

Filling this research gap provides, not only a theoretical contribution, but a practical one as well, because a deep understanding of P2X development from currently uncovered viewpoints can obviously facilitate the P2X R&D&I process and plant deployment. This work contributes to this field in the following ways:

1. While previous studies mainly focused on the technical, economic, and environmental aspects of hydrogen-based technologies, to the best of our knowledge, this is the first study to highlight the applicability of network-based innovation management theory for hydrogen economy research. By doing so, this study concentrates on the segment of P2X technologies and provides an in-depth analysis of a P2X-related knowledge transfer and leverage case.
2. By synthesizing the introduced key theories, this study extends firm-level exploration-exploitation learning theory to the inter-organizational level.
3. Based on the supporting empirical data of this extension, a practical contribution is provided to P2X development, by (1) highlighting the different areas where exploitative and explorative knowledge transfer is needed among universities and industry actors, and (2) showing how digital knowledge platforms can facilitate knowledge flows among different actors in this segment.
4. Different interpretations and subjects of exploitation and exploration in the P2X segment; and the role of collaborating actors (universities, industry representatives, and central “system builders”) in exploitative and explorative learning are identified during P2X technology development.

The study is structured as follows. First, we present the research framework, including the focal P2X technologies and the role of knowledge-sharing between industry representatives and universities in taking steps toward the hydrogen economy. The third part shows how the extended case study can be a useful contribution to the theory (of the development of the hydrogen economy) and what data gathering and analysis practices have led to the research results. After that, the characteristics of the emerging inter-organizational and knowledge network will be presented in the Results section. It is followed by a discussion of the interpretation of the results according to previous literature findings and theories. Finally, the last part describes the implications and the limitations of the study, and directions for future research.

2. Materials and Methods

2.1. Theoretical Background

As innovation management-focused research could cover numerous topics, regarding (1) its main related management areas (e.g., knowledge management, project management or process management) [16,17], or (2) its operational practices (e.g., innovation strategy planning, benchmarking, technology portfolio management or competency management) [18], the starting point must be clearly defined. The research is built on two key theoretical assumptions and two current calls for empirical research into innovation management.

Regarding the key theoretical assumptions, first, according to Teece [19], certain technological advancements (innovations) require complementary resources to utilize them in the market; however, these complementary resources (for example knowledge) can be granted by external actors (partners), as well. This leads to the trans-organizational or

inter-organizational innovation concept. In this sense, Millar et al. [20] suggest that trans-organizational innovation has increased complexity, as mutual learning and knowledge generation are distributed across disciplines and organizations. It can mean, for example, that a P2X developer company does not have the capacity and/or competency to conduct additional research related to the core P2X technology, but university research centers could provide new knowledge in the focal topic to increase the energy efficiency of the whole energy conversion process.

Second, strategic ambidexterity requires efficient operation in current business areas (exploitation) and also renewal and innovation in new business areas (exploration) [21]. This exploitation–exploration dilemma (i.e., how to allocate resources, focus attention, and balance them) is present in learning activities as well [22]. In this sense, organizational learning must also be defined from a strategic approach: “the process of improving actions through better knowledge and understanding” [23] (p. 803). Here it can mean, for example, that there are already well-known technologies, and exploitative learning would focus on industrial practices by which the technological potential can be exploited. On the other hand, there can be new technologies with numerous uncovered technical aspects which should be researched using explorative learning.

This study is also responding to the call from Nambisan et al. [24], as they analyzed inter-organizational innovation and its complexity considering digital technologies. In line with their suggestion, this research considers digital solutions as an orchestration tool that enables dynamic problem–solution matching within the distributed innovation process. It can mean, for example, that a digital platform could connect the actors in the inter-organizational innovative network, where knowledge regarding exploitation or exploration of technological opportunities can be dynamically transferred. Furthermore, even though numerous studies have highlighted the benefits of industry–university cooperation, Mascarenhas et al. [25] suggest that there is a clear need for research into “the process of partner selection and the way these innovation partnerships function” (p. 717). Addressing these aspects in this research narrows the scope to knowledge flows between industry and universities, so enables an in-depth analysis to be provided in the P2X segment.

Based on these theoretical assumptions and recent calls for research, this study focuses on the problem that P2X technologies are rarely implemented in grid-scale but, according to the theory, facilitating knowledge transfer and learning within an inter-organizational P2X innovation network could increase the pace of R&D and implementation. This topic (in this paper) belongs to the broader hydrogen economy development research area, which received increased attention from the research community in 2019 and 2020 (see Figure 1). The number of publications in academic journals that focused on hydrogen economy (based on their title or subject terms) was over 300 in 2020; and the three keywords (hydrogen, economy, and development) also appear increasingly often (based on the EBSCO database).

“Hydrogen economy development” as a whole, however, is less frequent. For comparison, Google Scholar listed more than 19,000 exact mentions of “hydrogen economy” since 2010, but only 119 for “hydrogen economy development”. Even though other terms instead of the “development” might indicate the same purpose, the open area for a further *direct* contribution is clearly visible. Addressing this issue as well, the research question is the following:

How could the pace of hydrogen economy development through P2X innovation-focused, digital inter-organizational knowledge networks containing industry actors and universities be increased?

Figure 2 shows the research framework.

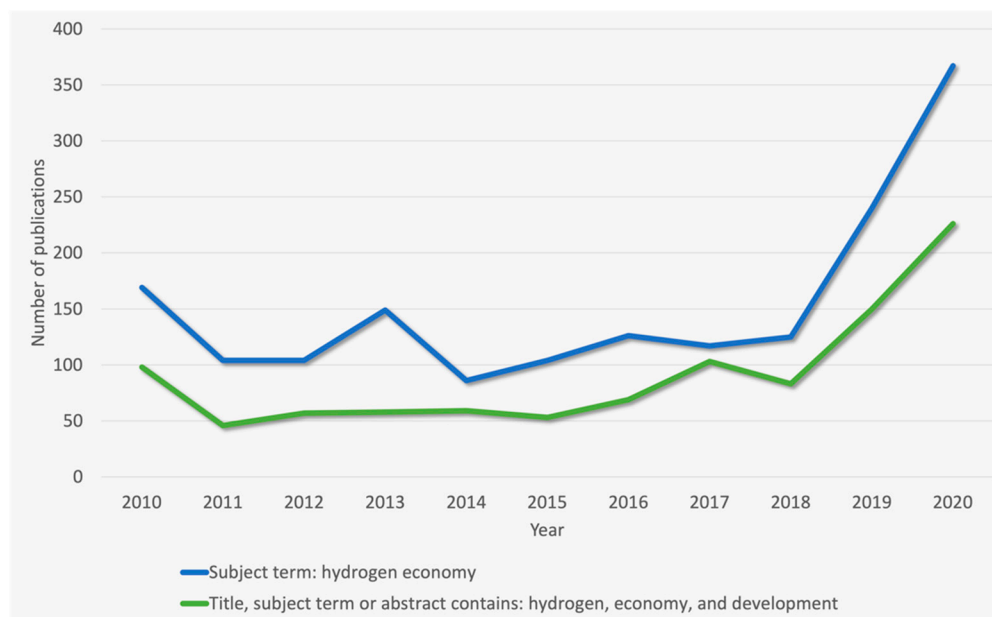


Figure 1. Publications in peer-reviewed journals focusing on hydrogen economy and its development (own construction, based on the EBSCO database).

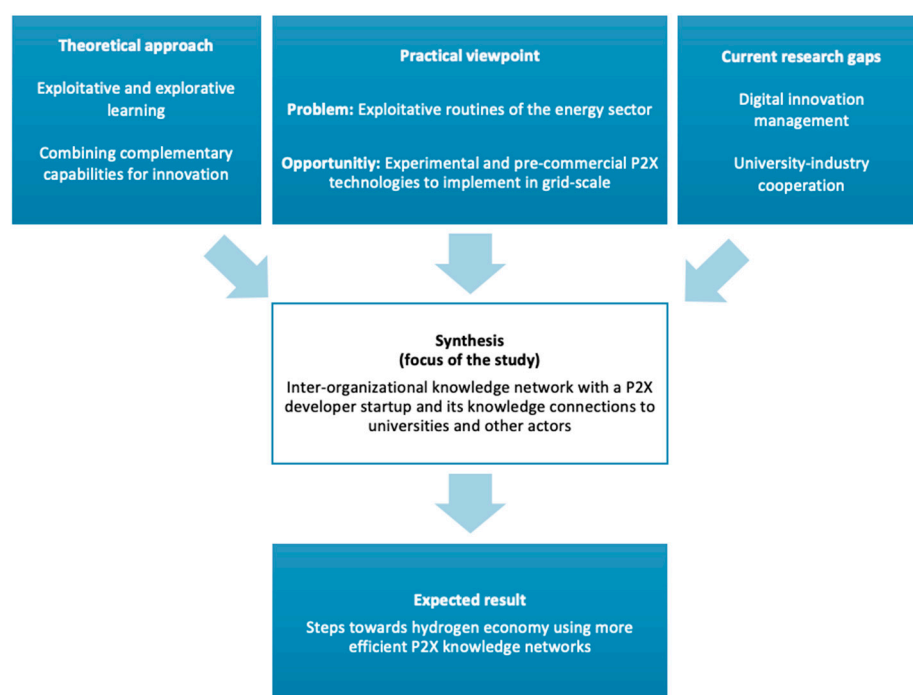


Figure 2. Research framework.

By conducting predominantly qualitative research, aiming to support practice with existing theories, but also to develop new theories that are built on practical experience [26], a presumption can be determined instead of a hypothesis. The presumption for the research question is that a digital platform could support the P2X technological know-how flows and so hydrogen economy development with academic and industrial partners, where universities would provide explorative knowledge (mainly because of their research capacities), while energy companies would provide exploitative knowledge (mainly because of their exploitative routines and extensive knowledge of existing businesses and infrastructure).

Besides the theoretical foundations of this presumption, the following sections show what different P2X technologies can be relevant for exploitative or explorative learning, and why collaboration between universities and industry representatives in the P2X segment should be analyzed in depth.

2.2. Power-to-X and the Focal Technologies of the Research

The power-to-X (P2X) concept is mainly characterized by the chemical conversion of surplus renewable electricity into other energy carriers. The concept emerged as a reaction to the need for long-term, large-size energy storage that cannot be efficiently achieved using, for example, batteries or compressed air storage [27]. The main functions of P2X technologies are (1) energy storage, because of the unpredictability of renewable energy production, (2) a carbon-neutral energy carrier or fuel, thus (3) reducing CO₂ emission [28]. The first step of the P2X process chain is the power-to-gas (P2G) process, which can be followed by a gas-to-chemicals, a gas-to-liquid, or a gas-to-power process; in this latter case realizing a power-to-gas-to-power conversion [29]. This study focuses on the P2G and P2L processes of the P2X. In the case of P2G and P2L, water electrolysis is the first step to producing renewable hydrogen (power-to-hydrogen, P2H). By staying in the P2G segment, it can be followed by methanation to produce renewable methane (power-to-methane, P2M), while hydrogen can be used to create liquid hydrocarbons (e.g., diesel, kerosene) in the P2L segment. Figure 3 shows the relevant P2X technologies for the research.

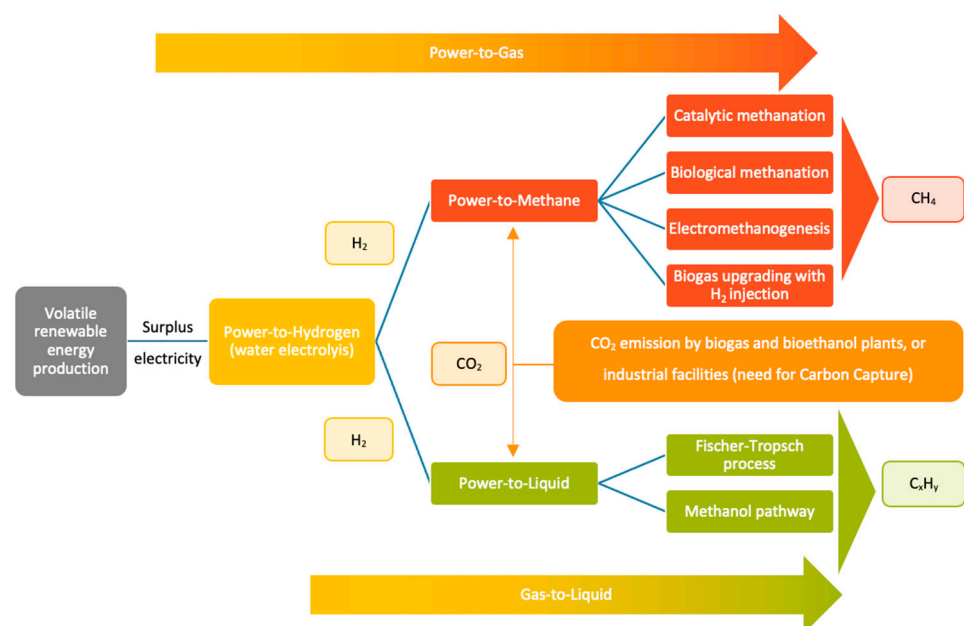


Figure 3. Relevant P2X technologies in this research, based on [3,29].

Based on previous research, these technologies can be crucial regarding the hydrogen economy and decarbonization efforts in several countries. For example, Blumberga et al. [30] showed the promising role of P2H and P2L in utilizing surplus renewable energy production to cover the electricity needs of Latvia; Bellocchi et al. [31] discussed how the increase of renewables improves the P2G and P2L viability for decreasing CO₂ emission in Italy; Mesfun et al. [32] presented how P2G and P2L technologies can contribute to integrating renewable energy sources by providing physical links between different sectors (electricity, transportation, heating) in the Alpine region. In addition, a recent study also demonstrated how the coupling of electricity and gas sectors by P2G plants at wastewater treatment plants can enable seasonal energy storage, which is promising due to the remarkable capacities of the natural gas grid in Hungary [10].

From a technological aspect, these solutions have been extensively analyzed. In the P2H segment, scholars compared alkaline (AEL) and polymer electrolyte membrane

(PEMEL) electrolysis regarding their operation in large scale, lifetime or flexibility [33–39] solid oxide (SOEL) electrolyzers [35,40,41] as well. In the P2M segment, CO₂ conversion efficiencies of biological and chemical methanation were evaluated several times [9,33,34,42–44]. Moreover, other directions, such as a bioelectrochemical system for electromethanogenesis [45] and producing methane by hydrogenotrophic methanogens in mixed culture [46] were also explored. Regarding P2L, its fundamental characteristics have also been studied [3,37] but, unlike AEL, PEMEL, chemical and biological methanation, which are already applied in grid-scale, there are mainly demonstration plants and research and development projects using P2L technology. The plan for the deployment of the first commercial-scale P2L plant was published in June 2020 using the technology from Sunfire GmbH [47].

Based on the above, technical and economic aspects have already received much attention, but business-, strategy-, and innovation-oriented research did not so far in the P2X segment, despite its vast significance (i.e., companies will invest in P2X technologies and utilize them).

2.3. P2X-Oriented Industry-University Collaborations

Based on previous research, to promote the development of the sustainable energy sector effectively, multiple knowledge and data sources must be synthesized; collecting and organizing relevant knowledge is crucial for the whole sector [48,49]. Organizations in this field should develop more inter-organizational R&D collaborations, which would provide them with more external knowledge (both scientific and technical) [50], while taking an integrative approach would also allow the integration of sources and the formation of alliances, and thus make their connection with policymakers easier [48]. At the same time, promoting collaboration between stakeholders, often with the support of digital technology, plays an increasing role in creating and preserving value, reacting to public demand, and striving for sustainable solutions. This is relevant not only in the case of for-profit organizations (e.g., a technology developer startup or a large energy company) [51] but in the public sector (e.g., a university) as well [52,53].

These inter-organizational R&D collaborations, involving industry representatives and universities, are relevant in the P2X segment as well. For example, the above-mentioned technologies are often developed and implemented in demonstration plants or commercial-scale plants through inter-organizational collaborations. A recent study showed that, over time, dyadic collaborations can lead to a formation of an innovation network in Hungary [8]. In such a network, actors combine their complementary capabilities (e.g., core technology from an innovative startup, broad industry knowledge and resources from a large energy company, scientific knowledge and research capacities from a university, or financial resources from strategic investors) to exploit the potential of an innovative P2G technology [8]. Based on previous literature, official announcements, and project deliverables, these collaborations are common within the international P2X segment of the energy sector as well. Table 1 shows examples of P2X projects where industrial companies have been working together with partners that were capable of completing industrial research and development (R&D) using scientific knowledge.

Table 1. Examples of P2X projects with collaborations among industrial and scientific actors, including universities.

Project	Location	H ₂ by:	Additional Conversion	Unique Attribute	Industrial Knowledge	Scientific Knowledge	Sources
H2orizon	Hardthausen am Kocher, Germany	PEMEL (880 kW)	-	Mobile H ₂ storage in a trailer	ZEAG Energie AG	German Aerospace Center (DLR)	[54,55]
REFHYNE	Wesseling, Germany	PEMEL (10,000 kW)	-	Largest P2H plant (under construction)	ITM Power, Shell, Sphera, Element Energy	SINTEF	[56–58]
Audi e-gas plant	Werlte, Germany	AEL (6000 kW)	Catalytic methanation	Largest P2M plant	ETOGAS, EWE Biogas, Audi	ZSW, Fraunhofer IWES	[36,59,60]
HELMETH	Kalsruhe, Germany	SOEL (15 kW)	Catalytic methanation	Innovative electrolysis technology	Sunfire, German Technical and Scientific Association for Gas and Water	Polytechnic University of Turin, European Research Institute of Catalysis, National Technical University of Athens	[36,59,61,62]
BioPower2Gas	Allendorf, Germany	PEMEL (300 kW)	Biological methanation	First commercial plant with biomethanation	Microbenergy, Viessmann Group EAM EnergiePlus, EnergieNetz Mitte	iDe (Institut of Decentralized Energy Technologies), DBFZ (German Biomass Research Centre)	[36,63–65]
BioCat	Avedøre, Denmark	AEL (1,000 kW)	Biological methanation	Patented microorganism and largest biomethanation plant	Electrochaea, Energinet, Hydrogenics, NEAS Energy, HMN Gashandel A/S, Biofos A/S, Audi, Insero	University of Chicago	[36,66–68]
Underground Sun Storage	Pilsback, Austria	AEL (500 kW)	Biological methanation	Underground methanation	RAG, Verbund, Axiom	University of Leoben, University of Natural Resources and Applied Life Sciences Vienna, Energy Institute at the Johannes Kepler University	[69,70]
STORE&GO-Italy	Troia, Italy	AEL (200 kW)	Catalytic methanation	P2M with CO ₂ from Direct Air Capture (DAC)	Climeworks AG (DAC), Studio Tecnico BFP, Engineering Ingegneria Informatica SPA, Iren SPA, ATMOSTAT, Hysytech S.R.L., Comune di Troia	Politecnico di Torino, CEA French Alternative Energies and Atomic Energy Commission	[71,72]
Copernicus P2X project	Karlsruhe, Germany	SOEL (10 kW)	Fischer-Tropsch synthesis	P2L with CO ₂ from Direct Air Capture (DAC)	INERATEC, Climeworks, Sunfire	Karlsruhe Institute of Technology	[73–75]
C3 Mobility P2L plant	Freiberg, Germany	N/A	Methanol synthesis	12 tons of green fuel already produced for tests of car manufacturers	Chemieanlagenbau Chemnitz, Mitsubishi Hitachi Power Systems Europe	TU Bergakademie	[76,77]

Table 1 illustrates that all the examined P2X sub-segments (P2H, P2M, P2L) can be characterized by collaborative R&D activities; moreover, that the valuable scientific knowledge is mostly provided by universities or research centers. Based on the importance of industry–academia collaborations in P2X R&D and innovation projects, but the lack of research into the dynamics of knowledge flows within these collaborations, researching

this area can have practical contributions for P2X developments and transition to the hydrogen economy.

2.4. Methodology

2.4.1. Extended Case Study Method

The research question is answered through the extended case study method, which builds on the retrospective analysis of a company and aims to gather in-depth understanding using quantitative and qualitative data, documents and interviews. Furthermore, the extended case study method involves constant iteration between theory, data collection and analysis in order to extend an existing theory [78,79]. In this study, the case study was conducted at a Hungarian P2X technology developer startup, which was founded in 2016. This startup company developed an innovative P2G prototype in 2018, and recently opened its research and development activities to the P2L segment as well. The company plans to use its special know-how to implement P2X technologies in grid-scale, producing renewable hydrogen, synthetic methane or liquid fuels. The company is also a member of the National Hydrogen Technology Platform in Hungary. Based on the theoretical background, the data collection and analysis were focused on technological knowledge flows and knowledge development from 2016 to 2021 through the inter-organizational connections of the company, especially with universities and other industry actors.

The company was chosen based on its information intensity [80], because an extended case study can only be prepared with sufficient information; moreover, international P2X projects suggest that there is a central technology development company that acts as the “engine” of the projects (e.g., Electrochaea in the BioCat project, Sunfire in the Copernicus P2X project, and Microbenergy in the BioPower2Gas project). Besides the necessity of information intensity for the case selection, based on Burawoy [78] and Danneels [79], an extended case study can be characterized by the following considerations:

It focuses on getting to know a case in-depth, emphasizing the past as well, not just analyzing the present.

The use of quantitative and qualitative data sources with interviews, reviewing the events chronologically, and exploring their circumstances.

Data from a longer study period are analyzed and compared with the theory, from which theoretical constructs are derived. These are finalized by reinterpreting the data and comparing it with existing theories, by collecting new data, and creating new constructs when the points of the data and the theoretical framework show a solid fit [78,79].

2.4.2. Data Gathering and Analyses

In line with the balancing nature of the extended case study method (between interpretative “understanding” and functionalist “theorizing”), the data gathering, and analyses had a predominantly qualitative and a supporting quantitative part, which were interconnected:

1. More than 30 semi-structured interviews were undertaken (with the employees of the company, stakeholders, and partners, including researchers at universities and managers of industrial partners), which lasted for 1–1.5 h. This is in line with research into similar strategic and management-related topics using the extended case study method. For example, Danneels [79] conducted 17 interviews, while Bingham et al. [81] and Tripsas and Gavetti [82] conducted 31 and 20 interviews. The interviews were guided by the main research question, considering that although Creswell [83] argued that qualitative questions come up and change continuously (in our case, partly based on the supporting quantitative analysis), even qualitative research cannot start without a plan; as such, some kind of a conceptional question is necessary [84]. The emerged sub-questions of the semi-structured interviews are listed in Appendix A. The interviews were coded using the suggested iterative approach (between data and theory) with regard to the extended case studies [79].

2. Quantitative text analysis was used on the content of the R&D Technological Platform of the P2X developer company, which contained 336 knowledge elements (documented technological know-hows, innovation-related questions and ideas, and e-learning materials) as a result of the open innovation processes of the company. Based on the supporting nature of this quantitative analysis, a representational approach (and not an instrumental approach) was followed instead to identify the intended meanings of the sources. The analysis-in parallel with the interviews-mainly involved thematic and network text analysis [85], but identifying trends was also relevant because of the extended case study methods. Based on these trends, future pathways could be also explored through interviews, as exploring scenarios is becoming highly relevant in the complex and uncertain future economic system [86].

The knowledge elements from the platform were first exported to Microsoft Excel with the year of the uploading (in line with the retrospective approach of the extended case study method), then the knowledge elements were categorized based on the interviews according to their:

- a. primary source (industry/academia);
- b. primary technological focus (e.g., P2H);
- c. primary (academic or industrial) sectoral connection (e.g., bio- or chemical technology);
- d. primary goal (e.g., benchmarking and market research).

The texts were analyzed using the JMP software, which can be used for text mining purposes [87]. Using the JMP software, the following steps were undertaken:

1. data cleaning (e.g., correction of grammatical errors);
2. tokenizing (removing punctuation and common words such as “the” or “some” using built-in Regex tokenization);
3. phrasing (a maximum of four words, but mostly from two or three words, e.g., “anaerobic digestion”, or “solid oxide electrolysis”);
4. terming (adding phrases to the term list) were conducted in the first part of the text analysis.

Regarding terming, manual recoding of the terms was needed because built-in stemming led (could have led) to distorted results (e.g., “active” and “activity” must not be grouped, in contrast to “activity” and “activities”). Manual recoding also allowed to group chemical symbols with their word (e.g., “H₂” and “hydrogen”), thus reveal trends instead of highly fragmented results. The main parameter of the analyses was the appearance rate of the different terms, and the analysis used the following tools to contextualize and guide the interviews:

1. Generating a document term matrix that showed whether a specific term appeared in a specific knowledge element or not and scoring terms by the attributes of the knowledge elements (e.g., their source or primary goal).
2. Generating and analyzing word clouds and trend analyses according to attributes of the knowledge elements, such as their source or upload year
3. Hierarchical clustering of the terms according to the attributes of their containing knowledge elements.

As indicated above, the interviews (the qualitative part) affected the text analysis (the quantitative part), but vice versa, as well as the documents and the text analysis affected the interview sub-questions (e.g., the importance of carbon capture was asked because of the volume of related know-how development in the platform). This interconnection is illustrated in Figure 4.

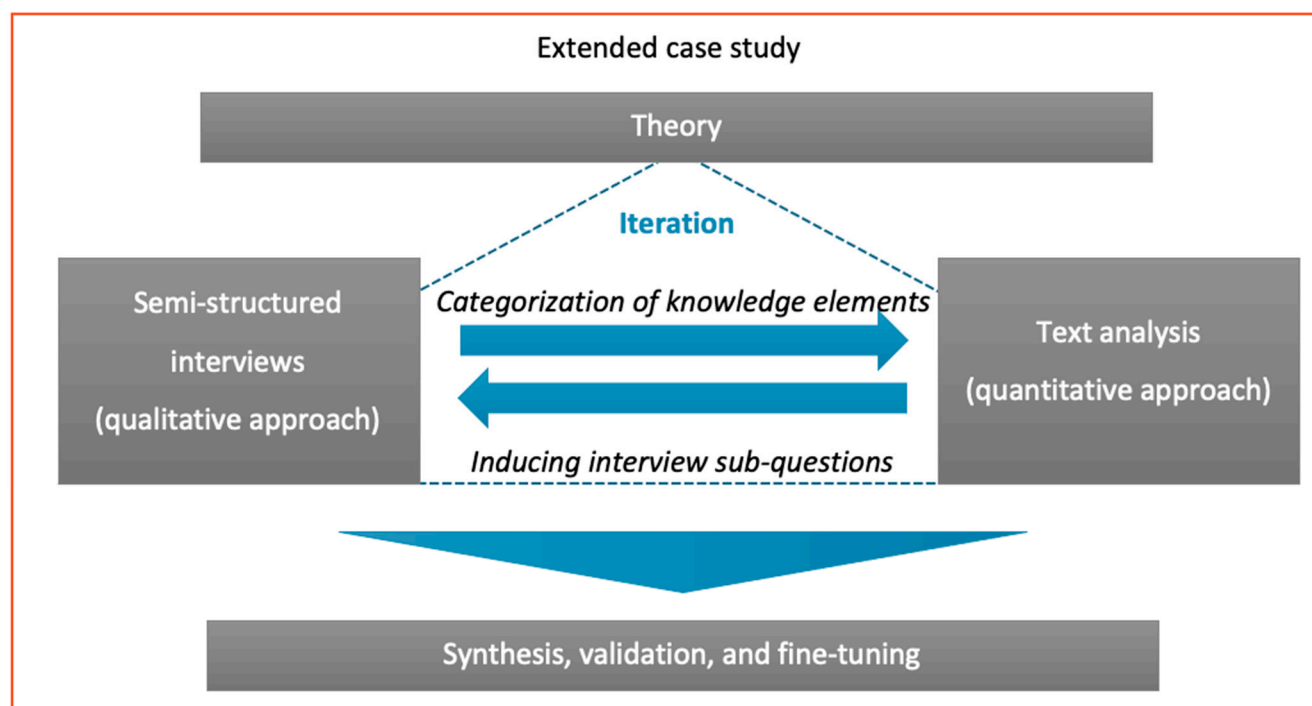


Figure 4. Research methodology (based on [79], extended).

Beyond these phases, the authors added a synthesizing, validating, and fine-tuning phase with the participants, which was an important step regarding the validity and reliability of the conclusions. Due to the interviewees' lack of time of the, this was only possible by sending a written summary of the main conclusions by email. Conclusions were finalized based on 19 feedback sheets.

Validity, reliability, and generalizability were considered in both a qualitative and quantitative sense:

1. To improve validity, the two-year-long research and the five-year-long time horizon were important to generate an in-depth understanding of the research area. The quantitative text analysis was needed to explore patterns in the knowledge base.
2. Reliability was improved by using more than one interviewer, which was important to balance between flexibility and consistency at the same time [88]. Moreover, the volume of the analyzed text was also extensive (335 knowledge elements (separate texts), 6345 terms, 84,285 tokens in total).
3. Generalizability was facilitated by the iteration of empirical data and earlier theories. It is important that, by following the iterative coding technique (similar to the grounded theory method), the authors could produce a substantive theory valid in a limited social context (e.g., innovative technology developments aiming at the hydrogen economy), rather than a more abstract, formal, general theory [89].

3. Results

3.1. Building an Inter-Organizational Network and a Digital R&D Platform

From 2016, the P2X developer company has consciously built more and more connections to university knowledge hubs, all of which support special areas of its operations (business and management, engineering, bio- and chemical technology, energy economics) and also provided opportunities for constant development of new knowledge. On the other hand, the growing number of industrial relationships revealed the company's need for applied (industrial) know-how development, which required partly the existing knowledge of the P2X developer company and also the accessed knowledge through universities. Recognizing its "bridge-like" role, the company has built its knowledge platform to facili-

tate internal R&D and open innovation as well. Figure 5 shows the inter-organizational knowledge network of P2X development.

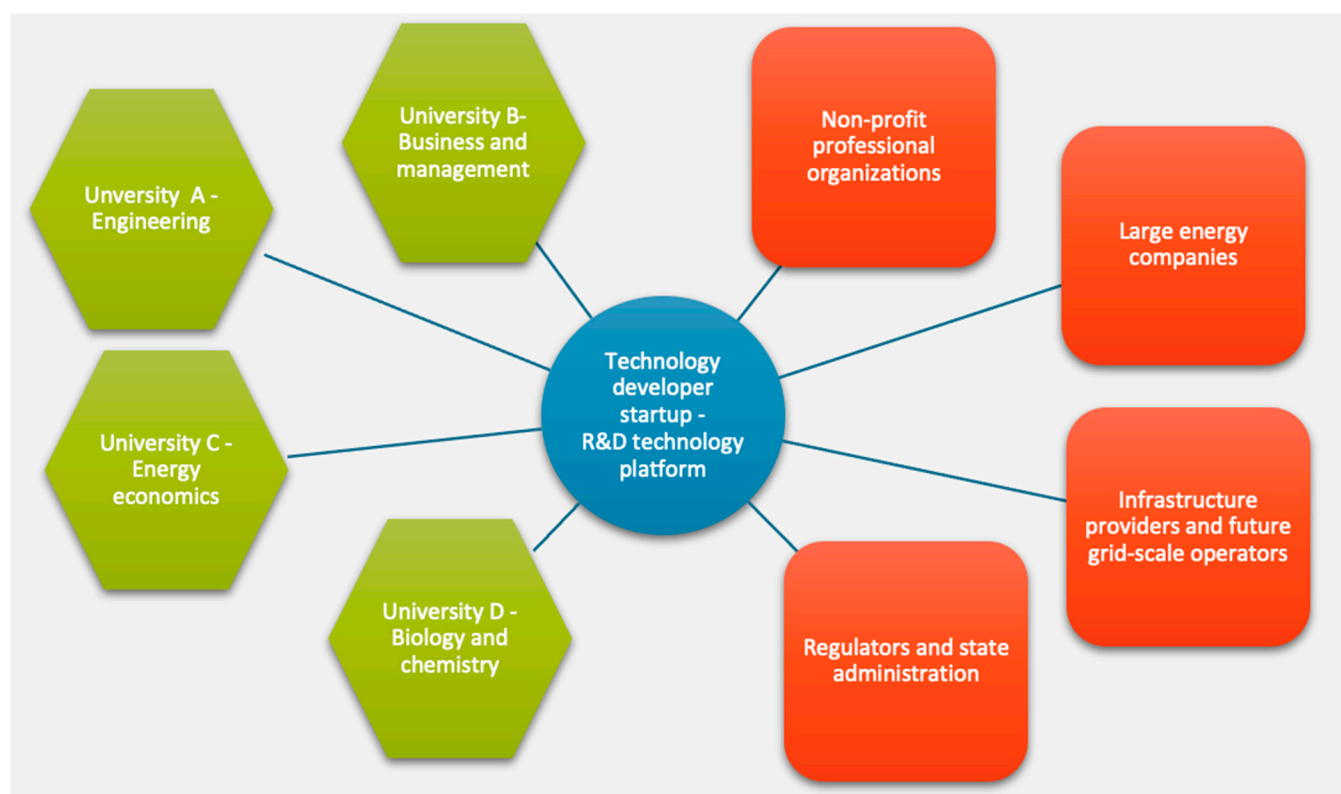


Figure 5. The emerging inter-organizational knowledge network of the P2X development.

In this platform, the company collected and developed the technological know-hows with its collaboration partners. The platform has three knowledge modules:

1. The “innovation problem solving/idea generation” module contains questions, answers, and ideas about current and further technological developments. These are the less mature knowledge elements.
2. The “digital know-how development” is useful for collaboratively codifying and developing know-hows, and collecting and storing data and information. These knowledge elements are more mature; these are, e.g., proven best practices or market data.
3. The “e-learning” module has the most mature knowledge elements; the e-learning materials, which provide concrete and proven guidance for prototype and (later) plant management.

The fourth module of the platform is the “prototype/plant management” module, which contains raw data about the prototype operations and provides remote monitoring and remote-control functions.

3.2. The Content of the Know-How Flows on the Platform

Regarding the content of these knowledge elements, dynamically changing word clouds can be seen. Figure 6 shows the word cloud based on the knowledge base of the platform, colored by the year of uploading the content (from green (2018) to blue (2021)). Considering the interviews as well, the main characteristics and dynamics of the know-how base are the following:

1. At the launch of the platform (2018), prototype operation, control issues, and analyses were in focus.

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Regarding the dynamics in the focus of know-how development, one can see from Figure 7 that the importance of carbon capture emerged because of the company's industrial partners. This figure also shows that

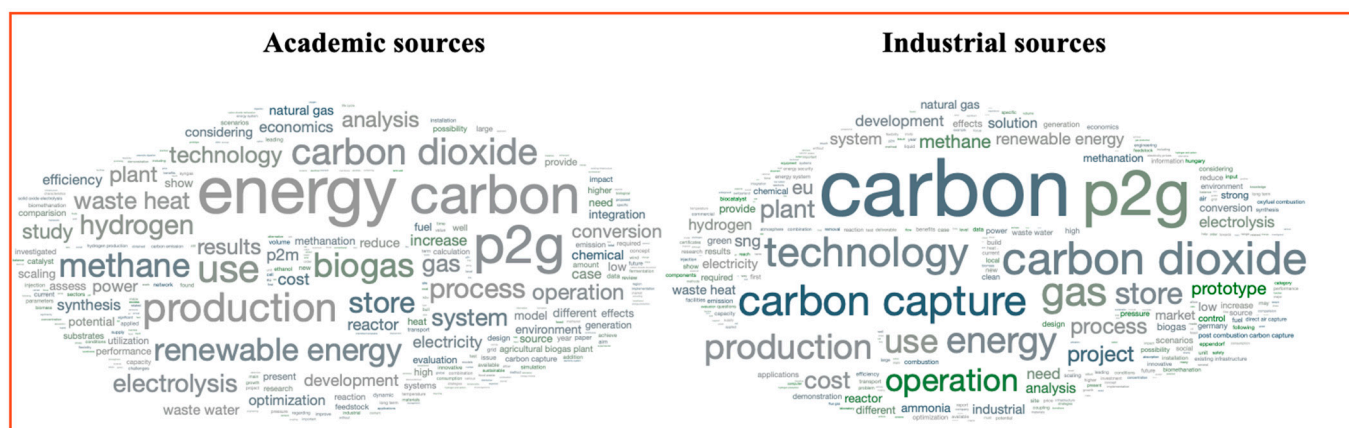


Figure 7. Academic versus industrial sources of knowledge elements (green: mainly 2018; blue: mainly 2021, grey: constant or mainly 2019–2020).

1. while academic influences on the know-how flows are divergent with smaller topics in higher volume, industrial influences are converging toward decarbonization;
2. the startup company has more connections to academic knowledge bases in the beginning but, with the development of the prototype and its own knowledge base, industrial partners have increasingly opened up for the startup. It resulted in further changes in the knowledge base.

These findings suggest that there is a clear need from industry towards a startup (or the startup ecosystems) and also the academic sector for creating efficient solutions for carbon capture. The interviewees also confirmed that industry actors are highly interested in carbon capture (CC) and utilization technologies because of the economic threat of the carbon tax or other costs related to CO₂ emission [91]. It is also supported by the primary sectoral connections of the knowledge contents, because carbon capture is mainly related to economics, business and management in the case of academic and industrial sources as well (based on the 50 most common terms, Figure 8). These sectoral connections of the knowledge elements were categorized based on the interviews.

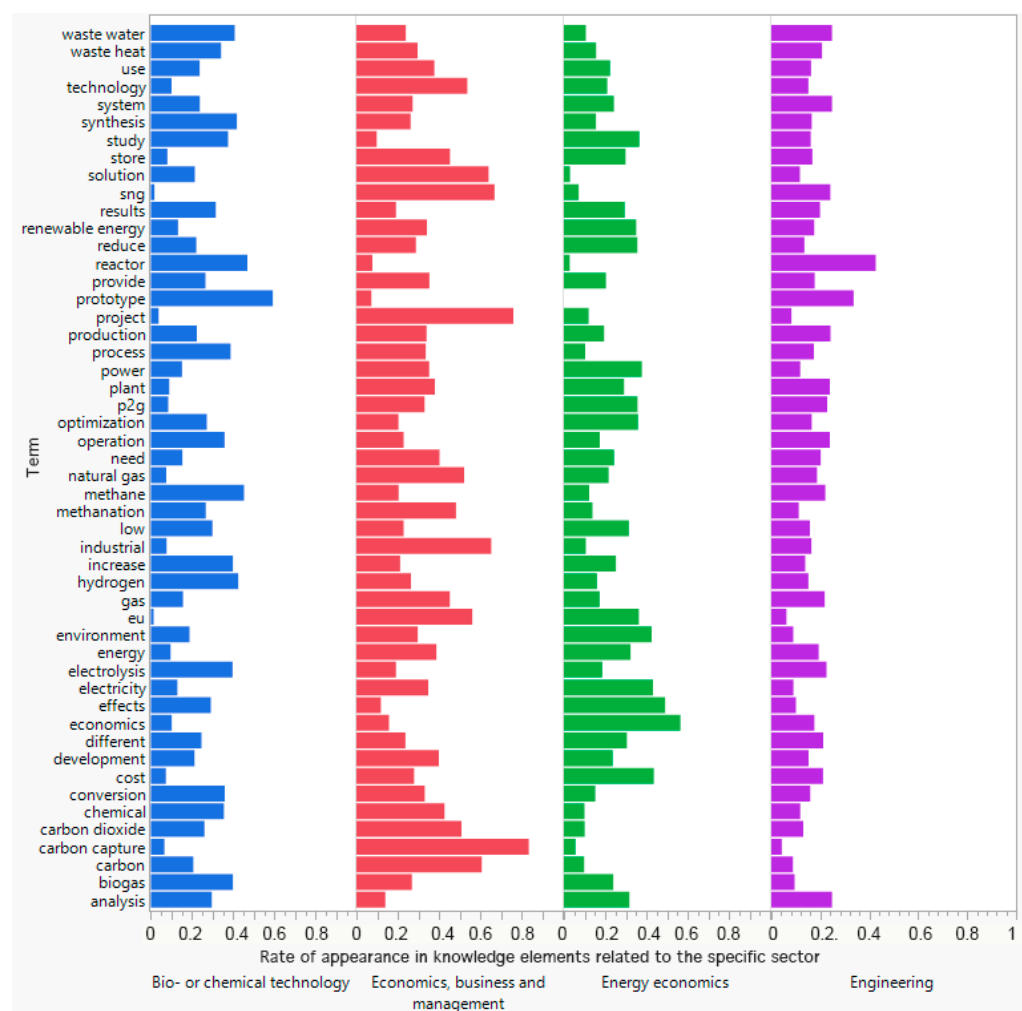


Figure 8. The sectoral connections of the most common terms in the knowledge base (based on the rate of appearance on the X-axis). For example, “carbon capture” appeared in “economics, business and management” related knowledge elements in ca. 80%.

3.3. Complementarities between the Knowledge Base of Industry Representatives and Universities

The results also suggest that academic and industrial knowledge sources during the know-how flows focus on different aspects of P2X technology development, i.e., comple-

mentary capabilities can be identified to profit from technological innovations [19]. Based on the terms that appeared at least 10 times in the database ($N = 649$) and the interviews with stakeholders, Figure 9 represents the appearance rate of the different terms (every dot represents a term) in knowledge elements with specific attribute combinations (e.g., industrial source, and bio- or chemical technological relatedness). The significance of this figure is that it shows the substantial complementarity between academia and industry regarding key areas of collaborative P2X technology developments. It meant a further step during the in-depth analysis, because it synthesized two former aspects with a new one: key topics based on the appearance rate (Figures 6 and 7) and the sectoral connection (Figure 8) with the source of the knowledge element. The figure shows that academic and industrial partners mostly have different strengths regarding sectoral connections.

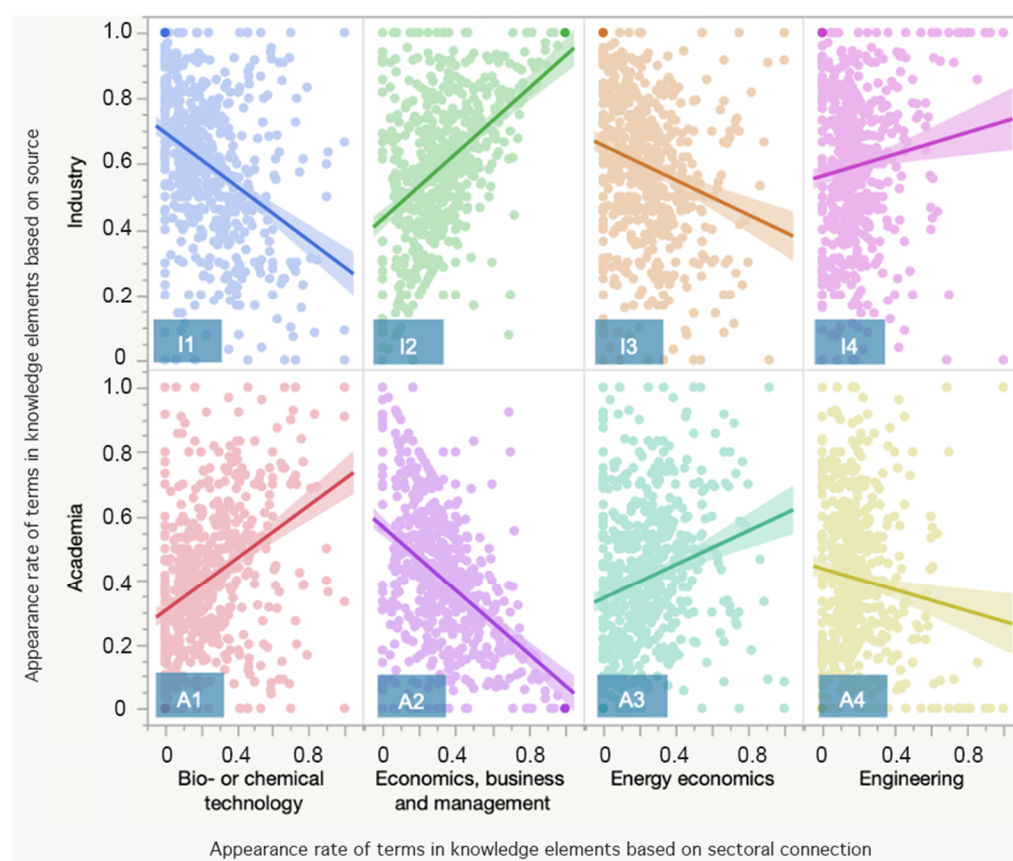


Figure 9. Appearance rate of the most common terms regarding their sources and sectoral connections.

1. Terms that often appear in know-hows from industrial sources are connected loosely to bio- or chemical technology (I1 cell in the Figure) or energy economics (I3), while know-hows from academia are often themed around these terms (A1 and A3).
2. Economics, business and management-related know-hows are mostly from industrial knowledge sources (I2), while academic sources hardly appear on these topics in the P2X segment (A2). This result can be explained by the early-stage nature of several P2X technologies, which are not sufficiently mature yet to generate business problems to be studied by researchers.
3. Regarding engineering, industrial sources were more dominant in the data, but this difference compared to academia is weaker. Based on the interviews, this is because the startup began its activity on a prototype level focusing on biotechnology, while engineering becomes (became) increasingly relevant when scaling up the technology.

These results suggest that universities and research centers mostly contribute to bio- or chemical technology-related energy economics-related areas at present, while industrial

partners affect know-how development from business and management, and engineering aspects. The synthesis of the raw data and interviews allowed the most important topics where industrial and academic partners can affect the development of P2X technologies in the future to be identified. Table 2 shows the main contributions and some of the most related terms (from the 100 most common) based on Figure 9.

Table 2. Potential contributions of industrial and academic partners in the P2X segment.

Industry	Using chemical absorption for carbon capture (e.g., “ammonia”, “prototype”, “control”, “operation”)	Developing decarbonization projects and producing clean fuels (e.g., “carbon capture”, “project”, “green”, “SNG”)	Gaining competitive advantage on EU markets by reducing energy costs, introducing novel, more energy efficient applications (e.g., “eu”, “market”, “cost”, “scenarios”, “first”, “applications”)	Increasing efficiency using new solutions, implement them with higher pressure (e.g., “pressure”, “reactor”, “data”, “control”)
Academia	Modeling reactions, evaluating efficiencies (e.g., “reaction”, “performance”, “efficiency”)	Developing innovative business models with CCS/CCU technologies (e.g., “innovative”, “combustion”, “demonstration”, “carbon”)	Studying scenarios about integration and potential of relevant technologies (e.g., “assess”, “model”, “economics”, “comparison”, “potential”, “integration”)	Evaluation of efficiencies by scaling up, integration, and waste management (“integration”, “reactor”, “data”, “wastewater”, “waste heat”)
	Bio- or chemical technology	Economics, business and management	Energy economics	Engineering

Beyond the academia–industry and sectoral categorization, the knowledge elements were categorized based on the interviews according to their:

1. primary technological focus, which contained five categories: P2H, P2M, P2G (P2H + P2M), P2L, and CC
2. primary goal of the knowledge/know-how development (benchmarking and marketing research, business development, scientific research, technology development, training).

These categories indirectly suggest some exploitation or exploration potential. For example, better-known technologies, such as P2H with AEL or PEMEL, may belong to the exploitation of the current knowledge and that is why business development and training would be more relevant in their cases. In contrast, carbon capture may require more exploration with scientific research and technology development. However, the hierarchical clustering based on these categories, which may suggest some hierarchical structure about what terms tend to belong to exploitation or exploration, shows a more complex picture. The extended constellation plot based on the 50 most common terms and their interpretation based on the interviews is presented in Figure 10. The figure also indicates the emerging knowledge network for P2X development.



Figure 10. Emerging P2X knowledge network based on the most common terms and the interviews.

4. Discussion

Based on the iteration and synthesis of theory, qualitative and quantitative data collection and analysis, exploitative and explorative learning should be interpreted, and the role of collaboration partners should be analyzed.

4.1. Exploitative and Explorative Learning in the P2X Segment

The results suggest that exploitation and exploration can have several interpretations at sector level, company level and on different time horizons. At sector level,

1. exploitation can be interpreted as:
 - a. the utilization of the core technological know-how base of the startup company on a commercial scale (P2H and P2M with biological methanation). This interpretation is supported by the technology readiness levels (TRL) as well. For example, low-temperature electrolysis (AEL, PEMEL) are at TRL9 [92], and there are grid-scale P2M plants as well [43,44];
 - b. the incremental improvement of these core technologies to increase efficiency and consequently support the commercialization of these solutions (see point a.). For example, these tasks can involve the utilization of low-temperature waste heat [93], or different nutrition of the biocatalyst [94].
2. exploration can be interpreted as:

- a. developing new P2X technologies, especially P2L, which is only in the demonstration phase [95], but future investigations can focus on the Power-to-Ammonia (P2A) process as well [96];
- b. developing carbon capture solutions, which could solve the challenge of scaling up the methanation technologies, as sourcing CO₂ is a critical input factor [8]. Moreover, CO₂ can be also required for P2L processes. The main carbon capture strategies are well known (post-combustion, pre-combustion, and oxyfuel combustion), but there are different TRLs in the case of concrete solutions [97] and their implementation on a commercial scale is also rare.

Considering the fundamental characteristics of P2X technologies, these sector-level interpretations of exploitation and exploration have relevance in developing optimal energy storage systems. In this area, important scientific advancements were recently published that suggest that the wide range of the emerged technologies in the analyzed case for exploration and (later) exploitation are relevant at system level and in other cases as well. For example, Lai et al. [98] proposed a new framework for long-term electrical power system modeling, because different energy storage technologies need to be accounted for; Petkov and Gabrielli [99] analyzed P2H as a seasonal energy storage option in low-carbon multi-energy systems, where the interactions of energy carriers, such as electricity, natural gas (methane), hydrogen or heat can enable new value propositions; while Sánchez et al. [100] considered methane, methanol, dimethyl ether (DME) and ammonia to determine an optimal infrastructure to provide energy storage or use these outputs in other energy applications. In line with these approaches Figure 10 showed that exploration cannot only mean technological exploration (e.g., P2L in grid-scale), but innovative approaches to system integration; for example, P2G and fossil fuel power plants [101] or developing hybrid renewable energy systems using already known technologies (e.g., wind turbines, battery storage, internet of things and diesel generators) [102]. The same will be true with the integration of novel P2X technologies, fulfilling an energy storage role, regarding which future energy systems will certainly require (1) collaborative and (2) explorative learning in practice:

- (1) collaborative because of the heterogeneous knowledge base that is hardly owned by one company or university;
- (2) and explorative because of the complexity of these new, integrated systems.

At company level, exploitation and exploration however, depend on the previous and present activities of the focal organization. The difference between a startup company and a large energy company can be illustrative. For example, while P2M can mean the existing business for a startup company, the knowledge base of which must be efficiently exploited on a commercial scale, it can mean a new business for a large energy company, so P2M must first be explored and channeled into the business activity.

Finally, the focus on exploitative and explorative learning is never static, neither at sector level, nor at company level. While in 2016 P2H and P2M might have required explorative learning from a company, in 2021 P2L and CC technologies might be explored to (1) build a new business, (2) facilitate the exploitation of the core business, (3) or build on the core business (as shown in Figure 8).

4.2. The Role of System Builders, Academic Partners, and Industrial Partners

Prior research indicated that, to face the challenges of the transition to a potential hydrogen society with low (or zero) carbon emissions, cooperation on multiple levels is inevitable. At the supranational level, a global approach should be taken to tackle the global problem. International consensus is required, including clear standards and targets for the applied technologies, as well as a timeline, agreed by a wide range of countries and other actors, with the alignment of national policies [103]. Besides, for the development and implementation of sustainable energy systems, the cooperation of lower-level actors is also crucial. Companies in the renewable energy sector have to be able to collect, identify, organize and use relevant information and its sources to be

competitive [104]. Furthermore, multiple sources argue that, in the university-industry knowledge-sharing network, a multidisciplinary and practice-oriented approach should be taken with the involvement of academic institutions and local energy companies [105,106]. University-industry cooperation would not only allow firms to enrich their technical knowledge and facilitate research activities [50], but it would also strengthen the trust between universities and industries. Mutually proactive exchanges and joint knowledge creation between universities and the industry would also provide universities with crucial research infrastructure and integrate university resources to promote the development of the energy-saving industry [105]. This research showed, however, that a central actor (a system builder) might be needed to connect to academic and industrial partners. This is in line with the earlier consideration that the actions of multiple and diverse actors involved in related R&D and technology implementation activities are often misaligned [48].

System builders (local actors who drive the development and construction of a system, e.g., a technology developer startup) not only play a central role in the implementation of new sustainable technologies, but also in collecting relevant knowledge, as well as connecting and enrolling other actors and ensure collaboration between them [49]. This suggestion was supported by the presented empirical results, too, because the technology developer startup was needed to develop an integrated R&D platform and connect industry representatives and universities in Hungary, which have different strengths in the main sectoral connections (bio- or chemical technology, economics, business and management, energy economics, and engineering).

While system builders integrate exploitative and explorative learning and connect academic and industrial partners, it seems evident at first sight that universities and research centers contribute to exploration, while energy companies contribute to exploitation. Based on our empirical results, however, this is only partly true: the contribution to exploitation or exploration in the P2X segment by academia or industry depends on the level of interpretation of ambidexterity (sector level or company level). In the focal case, universities mainly focused on developing new solutions that can improve the overall efficiency of the P2H and P2M process chain (e.g., utilization of low-temperature waste heat). Even though it requires innovations, these technologies represent the existing business of the focal company, i.e., these developments support exploitative activities at company level. It supports, however, exploration from the aspect of the sector, because P2H and P2M have not been extensively implemented, neither in Hungary, nor worldwide.

On the other hand, the exploitative role of industrial actors can also be ambiguous. Even though they could provide extensive knowledge of current infrastructure and opportunities, in the focal case the industrial partners drive exploration by focusing their attention, and also the attention of the system builder startup and universities, on carbon capture. Moreover, the results suggest that industrial partners can actively participate in finding and implementing new solutions for carbon capture, which belongs to exploration from the aspect of the technology developer startup (system builder) and the sector, as well (as CC solutions are also rare, even pilot-scale ones).

In sum, universities could support the exploitative activities of technology developer startups and large energy companies, and large energy companies could support the explorative activities of universities and technology developer startups if they are connected within an “innovation ecosystem”. This is a dynamic and adaptive system, in which actors have different capabilities, roles, and motivations, but they collaborate for the success of the innovation process [107]. Considering that these knowledge processes could happen in the digital environment, this study showed that “digital innovation ecosystems” [108] are relevant in the case of the development of the hydrogen economy as well.

Figure 11 summarizes the findings based on the synthesis of data collection, analyses, and prior literature findings from the aspect of a P2X innovation ecosystem. As the subjects of exploitation and exploration are never static, the table only provides a “snapshot”, but underlines that the actors should bring about exploitation and exploration in cooperation, due to their complementary capabilities.

	Exploitative Learning Areas (Examples Based on Empirics)	Explorative Learning Areas (Examples Based on Empirics)	Dominant Sectoral Contributions (Examples Based on Empirics)
Academic partners (Universities, research centers)	Supporting the exploitation of core P2G technological know-how with incremental improvements for higher efficiency	Developing efficient CC solutions	Exploitation: Modeling reactions, evaluating efficiencies, studying scenarios about integration and the potential of P2H, P2M (P2G)
System builders (Technology developer startups)		Developing new methods of chemical conversions (e.g., P2L or P2A)	Exploration: Developing innovative business models with CC and P2L
Industrial partners (Large energy companies)	Utilization of core P2G technological know-how on a commercial scale	Supporting the development of CC and P2L solutions with infrastructural knowledge and financing	Exploitation: Gaining competitive advantage in EU markets by reducing costs, introducing new applications, increasing overall system efficiency using P2H, P2M (P2G) technologies Exploration: Developing CC and decarbonization projects and producing clean fuels for transportation or other sectors (P2L, P2A)
The innovation ecosystem as a whole	-	Exploration of new ways of system integration and operation using new technologies to contribute sustainability efforts in a broader sense	

Figure 11. Exploitative and explorative learning in a P2X-oriented innovation ecosystem.

4.3. Analyzing the Correctness of the Presumption

The presumption for the research question was that a digital platform could support the P2X technological know-how flows and so hydrogen economy development with academic and industrial partners, where universities provide explorative knowledge, while energy companies provide exploitative knowledge. Based on the extended case study using a five-year time horizon and a hybrid (qualitative-quantitative) methodology, the results suggest that the presumption is only partially true. Even though a digital platform could indeed support know-how flows between universities and industry for P2X and hydrogen economy development, the following points shade this presumption:

1. There is a need for a system builder (e.g., a technology developer startup), who connects academic and industrial partners, integrates and participates in exploitative and explorative learning activities at different levels (own company, large energy company, and sector level), and so facilitates the formation of a(n) (digital) innovation ecosystem for technological know-how flows.
2. Exploitation and exploration can have different interpretations at company level and at sector level. Even though P2X technology development as a whole means exploration for the energy sector or the innovation ecosystem, and certain technologies can be more mature, for certain organizations these technologies require either exploitative learning for startups, or explorative learning for large energy companies.
3. Universities could contribute to exploitative learning (e.g., in the case of the commercialization of P2H and P2M with incremental improvements for higher efficiency), and large energy companies could contribute to explorative learning (e.g., by driving the development of CC solutions) as well.
4. The subjects of exploitation and exploration change over time, both on a company and a sector level. While P2G meant exploration five years ago, it can mean exploitation today, as TRLs are high enough and business models become viable. CC, which could solve challenges about CO₂ input for P2M and P2L, thus facilitating the more extensive use of renewable hydrogen, became one of the key areas of exploration.

5. Conclusions

This research focused on how the pace of hydrogen economy development could be increased through P2X innovation-focused, digital inter-organizational knowledge networks containing industry representatives and universities. The main novelty of the results

is that academia is also capable of supporting the exploitation of more mature technologies, and large energy companies could also drive exploration. This conclusion extends their expected role (i.e., academia drives exploration and industry drives exploitation) in the P2X technology development processes. Furthermore, the findings also suggest that a third actor, a “system builder” may also be needed to integrate exploitative-explorative learning and facilitate the formation of a (digital) innovation ecosystem. The main contribution of these conclusions to the literature is the applicability of network-based innovation management theory for hydrogen economy research. This novelty also indicates, however, some limitations and directions for future research. The main limitation of the conclusions is that they are built on one extended case study. Even though iteration with earlier theories, data collection and analyses, triangulation in the data sources (interviews and text data), and also qualitative and quantitative methods were applied, this abductive approach only allows the generation of a substantive theory. It is valid in a special context (i.e., the (Hungarian) P2X segment) and does not represent a formal, general theory [89].

As this research can be considered one of the first steps towards the in-depth understanding of inter-organizational know-how flows for developing the hydrogen economy, further research could take an even deeper approach to analyzing how intra-organizational knowledge management of universities and large energy companies could contribute to the success of P2X-oriented innovation ecosystems. For example, exploitation and exploration require different knowledge management practices (e.g., generating or covering up structural holes in the knowledge network or the employee network) [109–111]. From a technical perspective, the integration of the analyzed technologies, such as power-to-gas using carbon capture solutions [112,113], might require a specific combination of exploitative and explorative learning, which can be also researched in the future.

Despite these limitations, the authors believe that highlighting the central role of the “system builder” of a digital innovation ecosystem, which allows the integration of exploitative and explorative learning at different levels, could serve as a model for technological contexts. Moreover, the explored areas (especially carbon capture), where exploitative and explorative knowledge transfer is needed in the present and the near future among universities and industry representatives, is useful, one hopes, to increase the pace of developing the hydrogen economy.

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Abbreviations

AEL	Alkaline electrolysis
CC	Carbon capture
P2A	Power-to-Ammonia
P2G	Power-to-Gas
P2H	Power-to-Hydrogen
P2L\	Power-to-Liquid
P2M	Power-to-Methane
P2X	Power-to-X
PEMEL	Polymer electrolyte membrane electrolysis
SOEL	Solid-oxide electrolysis
TRL	Technology Readiness Level

Appendix A

Interview questions:

1. Main (conceptual) question:
How could the pace of developing the hydrogen economy through P2X innovation-focused, digital inter-organizational knowledge networks containing industry actors and universities be increased?
2. Categorization of certain knowledge elements (20–40 elements/interviewee; with double checking the elements) according to their
 - i. primary source (industry/academia)
 - ii. primary technological focus
 - iii. primary (academic or industrial) sectoral connection
 - iv. primary goal (Categories in the case of ii–iv. attributes emerged continuously, and recoding was needed at the end of the data collection)
3. Topics of the emerging sub-questions
 - Reflecting on the categorization:
 - Why does *[the name of the knowledge element]* belongs to *[the mentioned category by the interviewee]*, rather than to *[an alternate category suggested by one of the interviewers]*?
 - How does *[the name of the knowledge element/a certain technological focus/a certain sectoral connection/a goal of the know-how development]* contribute to the development and/or implementation of P2X technologies?
 - Discovering the characteristics of the know-how development during the time horizon:
 - What inter-organizational connections does the company have, and how have these connections been developed?
 - How are inter-organizational know-how flows (knowledge development processes) managed?
 - What is the relevance of the digital platform?
 - What are the main benefits of the academia-industry connections for technology or business development?
 - How have strategic plans and innovation focuses changed over time, and what are the future plans now?
 - What do exploitation and exploration mean in the case of technology development and business development?
 - Reflecting on the results of raw text analysis:
 - What can be the reasons for the dominance of *[a frequent term]* in general?

- What can be reasons for the dominance of [a frequent term] [in a certain time horizon]/from the academic or industrial perspective/in the case of [one of the previously identified sectoral connection]?
- What are the possible areas where academia and/or industry representatives can contribute to the P2X development in the future?
- How and why can [a list from a certain group of terms based on hierarchical clustering] be interrelated?
- How and why can [a certain group of terms based on hierarchical clustering] be related to [another certain group of terms]?
- What technological solutions might require exploitative learning (i.e., focusing on the utilization of the solution in large scale), and what solutions might require explorative learning (i.e., many new ideas, finding new ways)?

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