Managing uncertainties arising from technological change induced by sustainability transitions.

Von der Fakultät für Wirtschaftswissenschaften der Rheinisch-Westfälischen Technischen Hochschule Aachen zur Erlangung des akademischen Grades eines Doktors der Wirtschafts- und Sozialwissenschaften genehmigte Dissertation

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Preface

Acknowledgments

"Our Heads Are Round so Our Thoughts Can Change Direction"
(Francis Picabia)

More relevant than ever, this quote is my valuable motto in life and an apt description of my time as a doctoral student and valuable advice when dealing with uncertainties (as we will discover in this document). I learned that pursuing a dissertation is never a linear process, nor is progress a constant flow. It is a meandering path of endeavor with both times of absolute standstill and quantum leaps. For me, it remained largely uncertain and unpredictable despite doing research in uncertainty management, which is an ironic but philosophical parable to life.

My dissertation came to life thanks to multiple people. First, I would like to thank my thesis advisor, Professor Dr. David Antons. He had an open ear, provided food for thought, and ensured I was steering in the right direction. He supported me in exploring new seemingly disconnected research pathways, which caught my interest but reminded me to keep the bigger picture in mind. Thanks to his guidance, I followed the right track and took valuable adventures. He was the academic constant during my PhD time. I also want to thank Prof. PhD Torsten-Oliver Salge, whose sharp mind, brilliant ideas, and skill to ask the right questions I learned to value during multiple paper finalizations and revisions. I also want to express gratitude to the two Post-Docs, Dr. Hüseyin Caferoglu and Dr. Christina Dienhart, with whom I have been lucky to work. Additionally, I acknowledge many fellow doctoral students and researchers I met during my PhD at the RWTH Aachen, the University of Cambridge, and multiple conferences. All of you gave valuable input, mental support, and inspiration to continue. Without neglecting the others, I want to especially thank Michael Millan, Lukas Torscht, Jan-Marco Nepute, and Florian Jovy-Klein. Additionally, my research would not have been possible without the many survey participants and interview partners whom I owe gratitude for taking their time. I wish to thank the *Studienstiftung des Deutschen Volkes,* which awarded me a doctoral scholarship. In addition to the financial support, the exchanges with others from this network were particularly enriching. McKinsey & Company not only provided me with resources and access to great minds but also gave me an undemanding leave of absence to pursue my academic endeavor. Finally, and most importantly, I give my greatest thanks to my family and friends, especially to my wife, Julia, who made this project possible with great love and unconditional support. Thanks!

Summary

The number of patents and ideas keeps multiplying while the perceived pace of technological development increases. At the same time, the start-up foundations rise, and the longevity of incumbents plunges. Obviously, incumbent firms are struggling with this new uncertain environment arising from the break-neck speed of technological change; they are either unable to identify these uncertainties and their interactions or cannot find suitable treatments. The problem becomes aggravated by sustainability transitions, disturbing entire industries, disrupting traditional business models, and pushing great numbers of new technologies into the mainstream. The literature on uncertainties arising from (sustainable) emerging technologies has only inadequately addressed these issues.

This dissertation aims to delve into specific dimensions of the uncertainty-treatment nexus and the multitude of interactions between the involved dimensions. Its primary goal is to improve understanding of effective uncertainty management amidst emerging technological shifts, especially in the context of sustainability transitions. To achieve this, I present three essays, each analyzing different aspects of and interactions within the nexus. In the essays, I use a mix of qualitative and quantitative methods.

Essay 1 clarifies uncertainties surrounding hydrogen as an energy vector in 2035 through scenario development. I develop an extension to the Delphi method to generate foresight for entire technology fields. Grounded in 19 exploratory interviews and more than 100 hours of effort from 65 participants of the Delphi studies, my methodology employs a unique scenario-creation approach. It clusters experts with similar underlying assumptions into groups to enhance the accuracy and depth of foresight generation to reduce associated uncertainties. Practically, I present two future scenarios, complementing existing Delphi studies on hydrogen (e.g., CIFS, 2021; Lee et al., 2022), which help policymakers and management navigate the evolving industry. I also find that taking a technology field perspective can generate novel insights into technology diffusion. Essay 2 provides an in-depth exploration of uncertainties faced by oil and gas incumbents during sustainability transitions, with a focus on the “discovery & search”, “experimentation”, and “flexibility & robustness” uncertainty treatment strategies. Expanding on the findings of Essay 1, which highlighted the significant role of oil and gas (O&G) companies in sustainable transitions, I conducted a longitudinal comparative case study involving five European O&G companies to investigate these inquiries. The essay documents the process of identity change through 23 semi-structured interviews and analysis of 40 internal and external documents. The study introduces the "theory of serendipity" (Busch, 2022) into the organizational change literature to illustrate the serendipitous nature of identity change

processes. I document how managerial agency, fortuitous occurrences, and environmental conditions influence how and when discontinuous identity trajectories occur. Furthermore, the essay examines how transformations of peripheral companies' domain identities deter industry-wide changes. Essay 2 presents a newly developed process model of sustainability-induced identity change, which provides practical guidance for management, policymakers, and shareholders on how to deal with uncertainties arising during sustainable transition.

Lastly, Essay 3 aims to elucidate incumbent behavior and its success in dealing with uncertainties from emerging technologies during technology entries. Building on the findings of Essay 2, which state that incumbents especially struggle to enter new technologies financially sustainably, I examine entry strategies from a portfolio standpoint and answer the following questions: Which timing strategy is beneficial for incumbents entering emerging technologies? How do different uncertainty treatments – particularly strategic planning rigidity and consistency – interact with diversification (technology entries)? This investigation utilizes a dataset comprising 386 venture capital (VC) funds. By combining the uncertainty reduction and entry timing perspectives, I show that early entry strategies yield superior financial returns, extensive information gathering often fails, and sectorial consistency is key in uncertainty reduction. I also identify three unique interaction mechanisms of uncertainty treatments: supportive, complementary, and competing.

Collectively, the dissertation offers a fresh perspective on how companies can effectively navigate the uncertainty-treatment nexus of emerging technologies. Its contributions (1) extend uncertainty management beyond individual technologies to encompass entire technology fields, (2) underscore the interplay between uncertainty types and treatment strategies, and (3) propose a proactive approach to managing unknown unknowns.

Dissertation Structure

This thesis is organized into two parts: Part A, the Synopsis, provides a joined introduction, research background, and dissertation purpose. It continues with summaries of each research essay and lastly holds a joined discussion elaborating on how they contribute collectively. The role of this part is to give an overview that connects the research papers and places them in the wider research field. Part B encompasses the three research essays that form my dissertation's core. Different in their methodological approach, they are all structured into an introduction, conceptual and contextual background, findings, and discussions for both theory and practical management.

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Part A: Synopsis

Introduction

Humanity has been confronted with uncertainties and their reduction since its genesis. However, increasingly rapid technological developments and resulting change are forcing ever faster adaptation and causing ever greater uncertainty among people, organizations, industries, and entire societies, making uncertainty management paramount (Kurzweil, 2014). These technological uncertainties arise from emerging technologies (Rotolo et al., 2015) and resulting innovations, which have also been recognized as drivers for economic growth (Dosi, 1982). Emerging technologies are radically novel, relatively fast-growing technologies that pose the potential to have a considerable impact, where the latter lies primarily in the future, making them uncertain and ambiguous (Rotolo et al., 2015). Their commercialization depends on commercializing actors, the diffusion of technologies in the market, the interactions with the innovation system, and the type of technology (Haessler et al., 2023). While the literature is fraud with varying definitions for uncertainty (Arend, 2024c), in this dissertation, I follow Knight's (1921) conceptualization, describing uncertainty as the lack of knowledge about an event's probability. After previously distinguishing only between high or low levels of uncertainties (D. Teece, 2007), research has evolved to unbundle emerging technology uncertainties into distinct categories: (1) technology uncertainty, (2) application uncertainty, (3) user uncertainty, (4) ecosystem uncertainty, and (5) business model uncertainty (Kapoor & Klueter, 2021). Similar has been done for uncertainty treatment strategies, which can be grouped into six buckets (Arend, 2024b).

Despite this, these theoretical advancements fail to comprehensively explain how incumbents behave when confronted with emerging technologies' uncertainties. This is particularly relevant in the case of emerging technologies in the context of sustainability transitions (Franke et al., 2023) where technologies tend to emerge in sync with other technologies, increasing complexity (Haessler et al., 2023; Rosenberg, 1996). How these factors interact and create value is complex and unclear to foresee (Kapoor, 2018); it thus requires particularly stringent uncertainty management (Gomes et al., 2022). Addressing emerging uncertainty necessitates acquiring information concerning the costs and revenue streams linked to a particular monetization model (D. Teece, 2010). Particularly, incumbents face challenges as traditional business models frequently do not seamlessly apply to emerging technologies (Amit & Zott, 2012; Snihur et al., 2018). Moreover, ecosystem and application uncertainties require incumbents to reconfigure their knowledge base (Eklund & Kapoor, 2019; Kapoor & Klueter, 2021); how they do so is unclear. Various treatment strategies exist (Arend, 2024b); together, these two perspectives – types of uncertainties and treatment strategies – open the field of tension for my dissertation, the uncertainty-treatment nexus. A deeper understanding of this nexus is required to fully comprehend incumbent uncertainty treatment strategies when faced with emerging technologies in the context of sustainable transitions. For example, (1) which interactions of companies with technologies reduce uncertainties, (2) what factors influence incumbents' ability to reconfigure their knowledge base during technology uncertainty, (3) when do diversification strategies yield beneficial uncertainty reduction, (4) how do incumbents make strategic commitments in the face of these uncertainties, and (5) what methods exist to create foresight when faced with multi-faceted uncertainty constructs.

This dissertation thus aims to examine existing research with fresh eyes and tackle specific dimensions of the uncertainty-treatment nexus. My primary objective is to enhance comprehension regarding the effective management of uncertainties amidst emerging technological shifts, particularly within sustainability transitions. This focus is crucial due to the distinctive characteristics that differentiate the dynamics of sustainability-driven changes from those of other emerging technologies. I do so via three essays, each tackling different parts of the nexus. Essay 1 aims to clarify uncertainties regarding hydrogen as an energy vector via a scenario development. Essay 2 features a deep dive into uncertainties during oil and gas incumbents' sustainability transition, emphasizing discovery & search, experimentation, and flexibility & robustness strategies. Finally, Essay 3 is targeted to clarify incumbent behavior and its success during diversification strategies from a portfolio perspective with the help of the uncertainty reduction theory.

The dissertation's findings yield three key implications for theory. (1) I extend uncertainty management beyond individual technologies to encompass entire technology fields, (2) I underscore the interplay between uncertainty types and treatment strategies, and (3) I propose a proactive approach to managing unknown unknowns. First, the dissertation highlights the interconnectedness of uncertainty types. For instance, Essay 1 illustrates how technological progress hinges on multifaceted applications and the concurrent evolution of supporting technologies in the case of the hydrogen industry in 2035. It challenges the conventional focus on singular technologies, advocating for a broader perspective termed "Technology Field Uncertainties," encompassing uncertainties from the principal and supporting technology domains (Haessler et al., 2023). This perspective emphasizes the complex web of interactions between technologies and their uncertainties, offering novel insights into technology diffusion. Second, the dissertation delves into uncertainty treatment strategies, revealing their interdependence. Essay 2, inspired by Busch's (2022) conceptualization of serendipity, explores how organizational identity dynamics influence the management of uncertainties. I delineate how the confluence of managerial agency, unexpected occurrences, and environmental factors influence the trajectories of organizational identity change and under which conditions advantageous discontinuous trajectories are more probable. From Essays 2 and 3, I find evidence for either supportive, complementary, or competing nature of these strategies. Third, while the uncertainty literature often portrays unknown unknowns as untreatable (Arend, 2024a), Essay 2 partially challenges this notion. I argue that companies can increase their "contact area" with luck through preparation, thus enhancing resilience against unforeseen events. This perspective reframes uncertainty management as increasing the likelihood of positive outcomes in the face of unpredictability. All findings hold valuable insights for policymakers and managers in dealing with uncertainties arising from emerging technologies and open several pathways for future research.

Research Background

Emerging technologies and innovation

Rooted in Schumpeter's idea of creative destruction (Schumpeter, 1976), emerging technologies and resulting innovations have been recognized as drivers for economic growth (Dosi, 1982), which finds reflection in modern national growth strategies and discussion about benefitting from (climate) change (Haessler et al., 2023). They have been subject to technology and innovation management research for decades, analyzing their impact on industries and ecosystems (Adner & Kapoor, 2016), their timeline of proliferation (Anderson & Tushman, 1990), and their roots (Levinthal, 1998). Their initial characterization as "smooth, cumulative advance" has been revised (Kapoor & Klueter, 2020) and they are instead now defined by periods of setbacks and obstacles (Kline & Rosenberg, 2009; Rotolo et al., 2015) forming waves of technological change (Levinthal, 1998). Rotolo et al. (2015) defined emerging technologies encompassing earlier conceptualizations (Rosenberg, 1996) and previously mentioned attributes. This definition already features the aspect of uncertainty, which I will elaborate on later.

> *"An emerging technology is a radically novel and relatively fast-growing technology [...] with the potential to exert a considerable impact on the socio-economic domain(s), which is observed in terms of the composition of actors, institutions, and patterns of interactions among those, along with the associated knowledge production processes. Its most prominent impact, however, lies in the future and so in the emergence phase is still somewhat uncertain and ambiguous." (Rotolo et al., 2015)*

Emerging technologies can but must not lead to innovation, two terms that are used in the literature interchangeably but present a different concept (Haessler et al., 2023). The latter describes the commercialization, which in turn depends on technological developments

(D. Teece, 2007), a commercializing actor, the diffusion of technologies in the market, the interactions with the innovation system (e.g., governmental support), and the type of technology (Haessler et al., 2023; Rosenberg, 1996). The latter can be clustered into principal – incl. generic and proprietary – and supporting technologies – incl. production and infra-technologies (Haessler et al., 2023). Researchers (e.g., Martin, 2016) criticized the group of principal technologies as being overrepresented in research. One example of a technology system constituted by different types of emerging technologies is the commercialization of electric cars (Stringham et al., 2015). Battery technologies, semiconductor materials, charging technology, etc., developed in sync to form the platform for commercialization in the form of electric vehicles. This view of understanding technologies as interacting received theoretical recognition (Sandén & Hillman, 2011) but lacks methods and interweaving with the uncertainty research. Especially in technologies supporting the sustainable transition of the global economy, a mix-up (Rosenberg, 1996) between technology systems and their supporting technologies is visible (Haessler et al., 2023). Systems like clean energy, electric vehicles, or hydrogen (as an energy vector) are pressed into existing concepts of technologies, even though they consist of different technologies. This makes the understanding of emerging technology proliferation essential for sustainability transitions to succeed (Franke et al., 2023). The arguments leave two questions unanswered: 1) How do emerging technologies interact to lead to innovation? 2) How and when do firms interact (partner, invest, cooperate in ecosystems, etc.) to optimize commercialization?

Uncertainties arising from emerging technologies

In many daily and business situations, there is a gap between the currently held and the aspired knowledge needed to make a "good" decision. This typical situation oozes uncertainty, a concept that is easy to understand but loaded with complexity and without a comprehensive definition (Arend, 2024c). Knight (1921) described uncertainty as the lack of knowledge about the probability of an event happening, which distinguishes the concept from a risk where the probability is known (Gomes et al., 2022). Uncertainties are multi-dimensional (Arend, 2024d) and can result from knowledge asymmetries driven by varying diffusion speeds (Akerlof, 1970; Dew et al., 2004). To encompass the different dissensions and definitions of uncertainty (Arend, 2024a) introduced a new typology structuring different types of it. Uncertainty derives from unknown and known factors. The former is an unknown unknown and thus not directly treatable. The latter is either a known unknownable (not directly treatable because the information cannot be obtained) or a known knownable (information can be obtained).

The diffusion of emerging technologies is fraught with such uncertainties (Rosenberg, 1996), and the incapacity to foresee the future ramifications of successful innovations, i.e., the uncertainties surrounding them, hampers profiting from them (Dosi, 1982). Technology and innovation management theories promise to support scholars and practitioners in better understanding and anticipating them during technology diffusions. Rogers' (1962) theory most prominently depicts the diffusion process as a characteristic S-curve pattern. At birth, a technology is not attractive for mainstream adoption, but steady enhancements lead to its proliferation. Subsequent work began to acknowledge the deficiencies of S-curves. Work on the scaling of technologies and innovation (Clarysse et al., 2011; Haidar et al., 2022; Wigboldus et al., 2016) challenged the conception of diffusion as a linear, unidirectional, and well-contained process while Kapoor and Klueter (2020) called for more explicit recognition of the "significant uncertainties" about where, when, and how (Adner & Levinthal, 2002; Anderson & Tushman, 1990; Dosi, 1982) technologies emerge.

For instance, scaling processes can affect (and be affected by) factors within and beyond the socio-technical system they are a part of, triggering positive or negative spillover effects for a potentially diverse set of stakeholders (Wigboldus et al., 2016). Consequently – intending to identify threats and opportunities – Kapoor and Klueter (2021) unbundled the uncertainties into *technology, application, user, ecosystem,* and *business model uncertainty*. Only a complete understanding of uncertainty types enables efficient management (Arend, 2024e). Technology uncertainty is driven by missing information about the evolution of technological development and scientific foundations (Nelson et al., 2015), which in turn must also be seen in the context of the development pace of alternative technologies (Anderson & Tushman, 1990). Application uncertainties, on the other hand, arise from a lack of clarity on how and where technologies can be used (Gruber et al., 2008). Especially, technologies that can be used in multiple applications create uncertainties since their value proposition often does not present itself (Chesbrough & Rosenbloom, 2002). This is directly associated with user uncertainties where companies ex-ante do not know whether and how fast users adopt a certain technology in a specific application and are willing to pay for it (Kapoor & Klueter, 2021; Robertson & Gatignon, 1998). Even success with early adopter users does not guarantee a later proliferation (Hall, 2006).

As described, technologies do not exist independently; their proliferation also depends on the innovation of other participants – e.g., suppliers, partners, regulators, and even competitors – in innovation ecosystems (Adner & Kapoor, 2010). How these factors interact and create value is complex and unclear to foresee (Kapoor, 2018); it thus requires particularly stringent uncertainty management (Gomes et al., 2022). How to best – most profitability – monetize an emerging technology posits the business model uncertainty. Solving this uncertainty requires obtaining information about potential costs and revenue streams associated with a certain monetization model (D. Teece, 2010). Especially for incumbents, issues arise since traditionally used business models are often not directly applicable to emerging technologies anymore (Amit & Zott, 2012; Snihur et al., 2018). Notably, the ecosystem, business model, and application uncertainties require incumbents to "reconfigure their existing knowledge base or routines, and firms may vary in terms of their ability to reconfigure" (Eklund & Kapoor, 2019; Kapoor & Klueter, 2021). How they do so and what influences this configuration is unclear. To complicate things further, different types of uncertainty can co-exist and interact. Kapoor and Klueter (2021) argue to "unbundle" that the different levels of uncertainties and understanding of possible interactions are paramount. They describe the uncertainty occurrence as (1) independent, where the resolution of one uncertainty does not affect another (pooled interaction), (2) one uncertainty needs to get solved before another (sequential interaction), or (3) two uncertainty sources influence each other (reciprocal interaction).

Managing uncertainties in emerging technologies

When decision-makers fail to see and address uncertainties arising from emerging technology, companies could (1) fail to identify chances for the technology in other applications and with different business models, (2) neglect to help the technologies innovation ecosystem to develop accordingly to support a technology scaling, and (3) misjudge the required resources to generate value (Kapoor & Klueter, 2020). Additionally, the risk remains that technologies do not even reach the phase of value generation (Fagnant & Kockelman, 2015). Managing these uncertainties is profoundly different from dealing with risks since the probabilities of occurrence are unknown, and insurance is thus unavailable (Packard et al., 2017). Hence, their management is vital to innovation management, and different strategies exist to achieve this (Gomes et al., 2022; Packard & Clark, 2020). Similar to the uncertainty reduction theory (URT) – which describes individual interactions – a high level of uncertainty triggers information seeking (Berger & Calabrese, 1975). In the firm context, this information-seeking can lead to strategizing. "Strategies exist because of uncertainties"; when companies strategize, they are thinking about potential actions and possible outcomes, which are the foundation for making a decision on which option is the "best" to follow (Arend, 2024e). Arend (2024e, 2024b) further argued that strategizing thus needs to encompass all dimensions of potential uncertainties and proposed a framework for treating uncertainties during decision-making processes. This framework structures the strategies for treating treatable uncertainties in six "buckets": (1) *Sharing the burden with cooperation and insurance or through diversification* targets to uncover the unknown through entities outside the focal company. This is achieved, for example, through horizontal and vertical diversification, alliances, joint ventures, or portfolio expansions. The idea is that more possible "touch-points" bring more and better information to reduce uncertainties (M. King & Kay, 2020). (2) *Discovery, search, and monitoring* aim to secure better knowledge to make the unknown known. This involves information gathering to make better and more informed decisions where the search can be local or distant, incremental or radical, and explorative or exploitative (Katila & Ahuja, 2002; March, 1991). (3) *Experimentation, Experience, Analysis, and Modeling* seek to reduce unknowns by actively trialing technologies and business models. The philosophies of minimum viable products in development processes (D. Teece et al., 2016), trial-and-error learning and bricolage (Furr & Eisenhardt, 2021), and corporate venturing (Covin et al., 2021) are rooted in this strategy. When then confronted with an analysis of the acquired information, companies resort to sensemaking (Waterman, 1990), resulting in a dominant narrative of how the information is to be interpreted (M. King & Kay, 2020). (4) *Adapting to outcomes through flexibility, options, and robustness* enables companies to prepare for specific events, which requires a rough understanding of possible future factors to be flexible and robust against. In the literature, this strategy is limited to known events with unknown probability of occurrence. The governing thought is contingency planning (Packard et al., 2017). Typically, startups are considered to have better capabilities in this dimension than incumbent firms (Rindova & Courtney, 2020). D. Teece et al. (2016) argue that flexibility is driven by the ability to recombine resources and rapidly modifiable organizational structures. (5) *Influencing the outcome through social construction and preemption* is backed by the idea that companies can actively influence actors – e.g., education campaigns for user groups – and thereby reduce uncertainty since they make the knowable known by "forging" the future (Townsend et al., 2018). (6) *Scenarios and simulations* do not make the unknown known but create information about what it possibly could be. The idea is to draw future scenarios and identify influence factors or trends through foresight methods and extensive simulations (Gausemeier et al., 1998). From this "pool" of possible futures, decision-makers can select those with higher probabilities of occurrence and plan accordingly (Packard & Clark, 2020; D. Teece et al., 2016).

To add additional complexity, I believe these treatments must be applied to the dimensions of uncertainty from the previous chapter. Together, these two perspectives open the field of tension for my dissertation, the uncertainty-treatment nexus (see Figure A-1). In this brief literature review, I have presented these two dimensions as a framework to conceptually explain emerging technologies' uncertainty treatments. However, I also highlighted areas where a deeper understanding of specific fields and entire columns or rows of the framework require better understanding. For instance, I argue that technologies must be conceptualized as technology fields for which foresight methods are missing, what company and technology interaction reduce uncertainty, what factors influence incumbents' ability to reconfigure their knowledgebase during technology uncertainty, when diversification strategies yield beneficial uncertainty reduction and more. With this endeavor I follow Kapoor and Klueter (2020) who called for research to tackle how "incumbents, startups, and diversifying entrants" are affected by uncertainties. Additionally, it remains unclear how incumbents behave and how they make strategic (sometimes opportunistic) commitments in the face of emerging technology-derived uncertainties (Kapoor & Klueter, 2021).

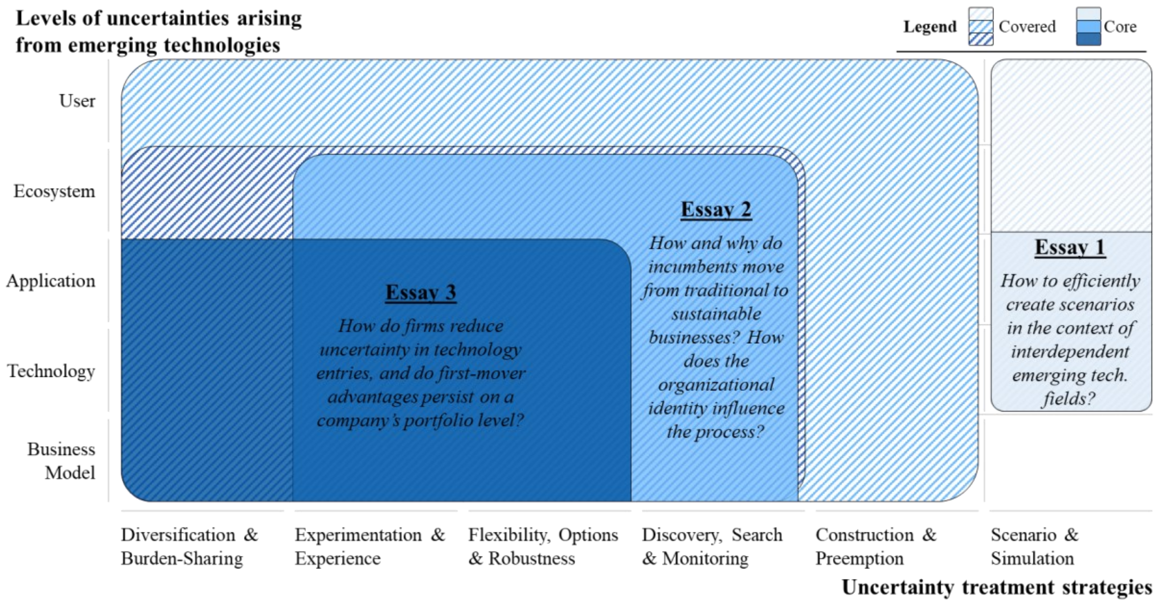

Figure A-1: Embeddedness of the essays in the uncertainty-treatment nexus (simplified research question in parentheses)

Due to these constraints within research on uncertainty reductions during emerging technological change, this dissertation aims to look at existing research with fresh eyes and to tackle specific dimensions (see coverage of dimension by essays in Figure A-1). The goal of this dissertation is to increase our understanding of how to manage uncertainties in the face of nascent technological change. I believe this is especially valuable in the context of technological change arising from sustainability transitions. Sustainable technologies need to replace other technologies, which are often still needed to satisfy human needs (Marchionna, 2018), often more performant and less expensive. Additionally, their pace of diffusion is tethered to the speed of societal sustainability transitions.

Summary of Research Essays

This chapter summarizes the research essays and highlights their principal discoveries. Each essay tackles a particular research inquiry, Table 0-1 offers an overview of these. Subsequently, a summary of each essay follows.

	Essay 1	Essay 2	Essay 3
Title	The Field of Hydrogen Technologies in 2035.	The Serendipitous Change Process of Incumbents' Organizational Identity.	Mastering Emerging Technology Entries.
Theme	Industry perspective on possible future scenarios for technologies constituting the hydrogen technology field	Organizational perspective on the change process of incumbents in the wake of sustainability transitions	Organizational perspective on technology entry strategies on a portfolio level
Research Gap	Lack of efficient foresight method for technology field evolution from and missing transparency on the future of hydrogen technologies	Incomplete picture of the organizational identity change process in the wake of sustainability transitions and its differences from other impetuses for change	Lack of understanding of first-mover advantages on portfolio level, the timing and the interaction of uncertainty treatment strategies
Research Question	How will the hydrogen technology field develop until 2035? How can we efficiently create future scenarios for highly interdependent technology fields?	How and why do incumbents move from traditional to sustainable businesses? Moreover, how does the identity change process unfold in their sustainability-induced transitions?	Which timing strategy is beneficial for incumbents entering emerging technologies? How do different uncertainty treatments interact with diversification?
Research Objective	Extent existing methods to applicability for technology fields	Extent theory on the dynamics of organizational identity change	Extent theory on diversification timing and uncertainty treatment strategy interactions
Theoretical Foundation	Technology strategy, technology diffusion, and technology interactions	Organizational identity theory and identity change processes, theory of serendipity	Uncertainty reduction, first and early mover advantages
Method (Design)	Newly developed Delphi-method extension (2 staged RT-Delphi) incl. automatic scenario generation	Longitudinal, comparative multi-case study during oil and gas companies' sustainable transitions	OLS (Ordinary Least Square) regression analysis with direct and moderated effects
Unit of Analysis	Industry Level (entire value chain of hydrogen economy)	Organizational Level	Organizational Level
Data Sources	19 interviews for Delphi preparation, 100h of effort generated by 65 experts participating	23 semi-structured interviews and 40 internal and external documents	386 VC fund datasets from Pitchbook® extended with +100k deal and investment datapoints
Pre-sentations	2022: Innovation Research Seminar, Aachen, Germany 2022: BAMM Research Seminar, Bielefeld, Germany 2023: Aachener Wasserstoff Kolloquium, Aachen, Germany 2023: R&D Management Conference, Sevilla, Spain	2022: Innovation Research Seminar, Aachen, Germany 2023: ISPIM Conference, Ljubljana, Slovenia[1] 2023: BAMM Research Seminar, Hanover, Germany 2024: EURAM Conference, Bath, United Kingdom	2024: iBAMM Research Seminar, Groningen, Netherlands
Status	Published in Technological Forecasting and Social Change	In finalization for submission to the Scandinavian Journal of Management	In finalization for submission to the Strategic Management Journal

Table A-1: Overview of research essays

1 Accepted but not presented due to illness.

Essay 1: The Field of Hydrogen Technologies in 2035
Insights from an Extended Delphi Approach

Global warming's acceleration has made its impacts increasingly dangerous and evident, prompting calls for a shift from fossil fuels to renewable energy sources to safeguard ecosystems (IPCC, 2022). Hydrogen emerges as a potentially pivotal energy vector in this transition, poised for significant global demand growth (Wang et al., 2021; Wappler et al., 2022). It finds use as a feedstock element in multiple industries today and is expected to replace fossil fuels in various others (Hydrogen Council, 2021; The Economist, 2021). However, widespread adoption hinges on overcoming technological readiness hurdles, cost reductions, and infrastructure development (Gül et al., 2019; IEA, 2022; Ren et al., 2020). Technology, user, application, and ecosystem uncertainties (Kapoor & Klueter, 2021) exist, complicating the answer in which applications hydrogen can become prevalent. Actors (e.g., policy and corporate decision-makers) need transparency since hydrogen's system-level success depends not on the proliferation of single technologies but on the evolution of a set of technologies (Markard & Hoffmann, 2016). Viewing hydrogen and its enabling technologies as an interconnected technology field – with complementary interactions between technologies – can reduce these uncertainties.

I developed an extension to the Delphi method, allowing me to generate foresight about the entire technology field and I applied this method to the field of hydrogen technologies in 2035. To do so I ran two interconnected Delphi studies: One focused solely on technological dominance and hindrance reasons, while the other addressed the related consequences. The research is built on 19 exploratory interviews and 100 hours of effort generated by 65 experts participating in the two Delphi studies. My unique scenario-creation approach clusters like-minded experts with similar underlying assumptions in groups.

Essay 1 presents two future scenarios about the technology field of hydrogen in the year 2035 and associated consequences, complementing existing Delphi studies on hydrogen (e.g., CIFS, 2021; Lee et al., 2022). I contribute methodologically to the technology foresight literature and build on the literature on technology interactions (Sandén & Hillman, 2011). I show that a technology field-level perspective can generate novel insights on technology diffusion. My approach could help researchers and practitioners in areas other than hydrogen leverage the Delphi method's potential to zoom in on technology interactions within and between fields. Finally, I derive implications for management practice and show pathways for future research.

Essay 2: The Serendipitous Change Process of Incumbents' Organizational Identity
A Longitudinal Comparative Case Study during Oil and Gas Companies' Sustainable Transitions

Sustainable transitions, crucial for addressing grand societal challenges, pose opportunities and threats for companies, challenging their organizational identity (OI) and limiting their perceived legitimate actions (Köhler et al., 2019; Loorbach et al., 2017). OI must evolve for sustainable transitions to succeed. The evolution needs to happen before business models can be altered, especially in the case of incumbents whose legacy identities shape their change process (Hamilton & Gioia, 2009; Schultz, 2022; Wood & Caldas, 2009). However, limited research explicitly addresses OI change during incumbents' sustainable transitions (Biloslavo et al., 2019). Understanding how and why incumbents transition to sustainable businesses and how the identity change process unfolds is essential in reducing associated uncertainties and promoting change.

In Essay 2, I built on the insight of Essay 1 that oil and gas (O&G) companies play a major role in sustainable transitions generally and in the hydrogen transition in particular. Consequently, I conducted a longitudinal comparative case study across five European oil and gas (O&G) companies to explore the above-mentioned questions. I documented the identity change process with 23 semi-structured interviews and 40 internal and external documents.

The study contributes by drawing on the "theory of serendipity" (Busch, 2022) to document the serendipitous nature of identity change processes and how managerial agency, fortunate coincidences, and the environment shape organizational identity trajectories. It finds that discontinuous trajectories are more likely under specific circumstances, such as when (1) a broadened identity reframes sustainability-induced change as an opportunity, (2) favorable market conditions for scaling sustainable business models exist, and (3) a sudden impetus discrediting traditional "business model"-supporting identities occurs. Additionally, the study examines how activities at the industrial, organizational, and individual levels interact to shape OI trajectories, particularly in the context of sustainability-induced change. I can show how transformations of peripheral companies' domain identities deter changes within the industry. Essay 2 contains a vivid, newly developed process model of sustainability-induced identity change. Ultimately, I highlight practical implications for management, policymakers, and shareholders, offering insights into oil and gas companies' sustainable transition dynamics, key events, driving forces, and barriers. I close by giving future research directions.

Essay 3: Mastering Emerging Technology Entries

How Timing in Uncertainty Treatments Influences the Performance of Incumbents' Technology Entries

Emerging technologies drive economic growth (Dosi, 1982). They are characterized by novelty, fast growth, and uncertainty (Rotolo et al., 2015). Companies face this uncertainty by diversifying, experimenting, and increasing adaptability (Arend, 2024a). Failing to do so can lead to missed opportunities (Kapoor & Klueter, 2020). Hence, companies seek new market entries to capitalize on emerging technologies (B. L. King, 2008; Kurzweil, 2014), with entry timing being crucial (Zachary et al., 2015). However, existing research mainly focuses on individual or cohort entries within specific industries, neglecting the broader perspective of incumbents managing technology portfolios (Agarwal & Bayus, 2004; Hawk & Pacheco-De-Almeida, 2013). This portfolio approach is vital for long-term growth despite uncertainties (Kapoor & Klueter, 2021; Markman et al., 2019). To reduce uncertainties, companies acquire information and plan strategically, though it is often ineffective when information is scarce (Arend, 2024b). In these situations, experience in the market can compensate for missing information, but emerging technologies, by definition, lack re-entry opportunities, emphasizing the importance of consistency in familiar markets (Guillen, 2002; Hilmersson & Jansson, 2012; Lamperti et al., 2020; Lieberman & Asaba, 2006; Simon & Lieberman, 2010).

Essay 2 shows how difficult emerging technology entries are for incumbents and how severely financially underperforming endeavors negatively impact companies' willingness to engage in sustainable technologies. Consequently, in Essay 3, I studied entry strategies from an incumbents' portfolio perspective, investigating the persistence of first-mover advantages, especially in interaction with uncertainty reduction strategies, especially strategic planning rigidity and consistency. To do so, I used a dataset of 386 venture capital (VC) funds. This allowed me to study the performance of uncertainty treatment strategies, primarily diversification, measured by internal rate of return (IRR), providing more meaningful insights than survival rates or market shares (Agarwal & Bayus, 2004).

My contributions are threefold: First, I extend first-mover advantages to the portfolio level, proving superior financial returns also on this level. Second, I show that an emphasis on extensive information gathering can negatively affect performance when entering emerging technologies, highlighting sectorial consistency's role in reducing uncertainties. Lastly, I identify interactions between uncertainty reduction treatments.

Discussion, Limitations, and Future Research

The goal of this dissertation was to advance the understanding of how to manage uncertainties arising from sustainability transition-induced technological change. This equips all actors – policymakers, organizations, and individuals – better for dealing with the uncertainties arising on different dimensions. In pursuit of this objective, I contribute theoretical, methodological, and managerial insights utilizing both qualitative methods, such as multi-case studies and Delphi analysis, as well as quantitative approaches, like regression analysis, to investigate and validate previously unaddressed challenges. I not only covered all uncertainty dimensions (Kapoor & Klueter, 2021) and uncertainty treatment strategies (Arend, 2024b) but also investigated different levels of analysis from the organization's perspective to the perspective of industry and society. Collectively, the three essays offer fresh insights into the persistent challenges companies face when confronted with uncertainties arising from emerging technologies. This dissertation is a case in point of how neither uncertainties nor possible treatment strategies for these shall be assessed independently. The results give organizational decision-makers actionable guidance to navigate uncertainties.

Theoretical (and Methodological) Implications

The findings and results of this dissertation suggest at least three significant implications for theory. First, Rosenberg (1996) stated that "the lack of knowledge about the relationships between the different dimensions of uncertainty precludes us from understanding the total effect of uncertainty upon technological change". Consequently, I can show the significant interaction effects between different uncertainty types across multiple emerging technologies. Essay 1 demonstrates that technological advancements depend on technologies' multifaceted utilization across various applications, exemplified by fuel cell technology in planes, cars, trucks, or stationary power units. Conversely, the widespread adoption of technology in a particular application, e.g., hydrogen heating, hinges upon the concurrent evolution of multiple technologies like advancements in hydrogen transportation (e.g., ammonia shipping), distribution (e.g., coatings for gas networks), storage infrastructures and hydrogen generation (electrolyzers). It is thus too simple to see uncertainties solely arising from the focal technology.

The emerging technologies literature distinguishes principal and supporting technologies (Haessler et al., 2023). Essay 1 has built on this notion by showing that existing foresight studies (e.g., in the case of hydrogen: CIFS, 2021; Lee et al., 2022) focused on the examination of individual (hydrogen) technologies and even though the necessity of viewing hydrogen as an integrated technology field exists. To establish this view, I followed theoretical advances in technology strategy (e.g., Kapoor & Klueter, 2021), technology diffusion (e.g., Anderson &

Tushman, 1990), and especially technology interactions (Sandén & Hillman, 2011) that highlight the need to account for the interplay between distinct technologies.

I was able to show that uncertainties arise from principal and supporting technology domains; I thus call to understand "Technology Uncertainties" as "Technology Field Uncertainties" encompassing arising uncertainties from technological developments of both supporting (production and infrastructure technologies) and other (related) principal technologies. As such, each of those technologies must be seen in its own field of uncertainties (ecosystem, business models, users, technologies, and applications), creating a complex web of uncertainty interactions. This is a relevant contribution because I object to the perspective that technologies must always be viewed in ever more granular terms (Haessler et al., 2023; Kapoor & Klueter, 2021). Instead, it is necessary to consider each technology and the resulting uncertainties in the entire field of interconnected technologies and their interdependencies and uncertainties.

Additionally, I showed that the suggested field-level perspective can generate novel insights on the future diffusion of hydrogen as an energy vector, which could not be generated by conventional approaches focusing on individual technologies. I illustrated the efficacy of conducting two interrelated and staged Delphi studies in enabling research to create foresight about the impacts of technology interactions – both within and across different technological domains – on the diffusion of technology and its ensuing ramifications. Exclusively drawing from Delphi survey data and generating consistent scenarios automatically, this methodology avoids the necessity for employing a multi-method approach or mapping underlying drivers exhaustively. My approach holds promise for researchers and practitioners across various domains beyond hydrogen. It enables them to leverage the Delphi method to scrutinize technology interactions and arising uncertainties within and across fields. This facilitates a deeper comprehension of the uncertainties that arise from emerging technology fields.

Second, like the discussion of uncertainty-type dependencies, the treatment strategies also do not exist independently. In Essay 2, building upon Busch's (2022) conceptualization of serendipity, I augment the literature on identity dynamics by revealing the frequently serendipitous nature of identity transformation processes. I delineate how the confluence of managerial agency, unexpected occurrences, and environmental factors influence organizational identity change trajectories. I describe that discontinuous trajectories are more probable: firstly, when a previously broadened identity reframes sustainability-induced change from a threat to an opportunity; secondly, when market conditions favor the scaling of trialed sustainable business models; and thirdly, when a sudden impetus undermines identities supportive of "traditional business models." Next to extending existing conceptualizations of identity change by elucidating the interplay between conflicting idiographic identities, the described process holds valuable insights for emerging technologies' uncertainty management. Figure A-2 visualizes the identified interactions of uncertainty treatment strategies with green (Essay 3) and blue (Essay 2) arrows. I show that incumbents who are confronted with pressure (uncertainty from application and user level) to engage with sustainability technologies either use "preemption and social construction" (greenwashing) or "discovery, search, and monitoring" strategies (see blue arrows). The latter path leads to an extended scope of possible experimentation, automatically increasing a company's "flexibility and robustness" because more experience, capabilities, and diverse resources are available to build upon in case of uncertainties (follow blue arrows from discovery and search). This treatment interaction is a sequential process where each treatment supports and enhances the next.

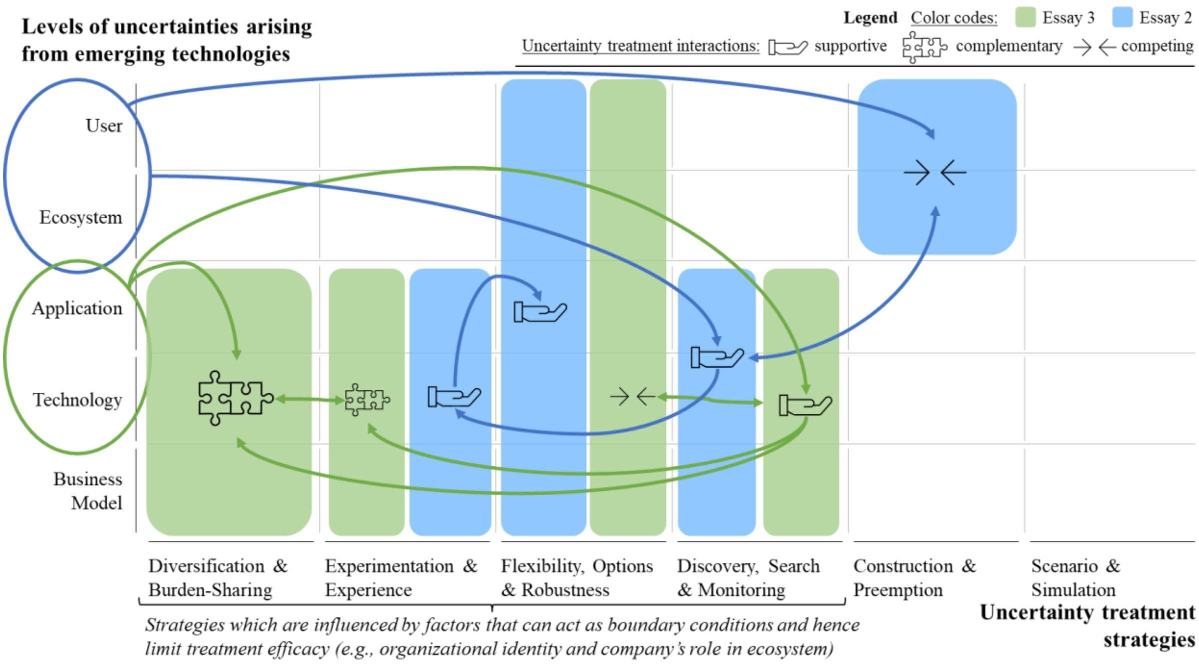

Figure A-2: Identified uncertainty-treatment interactions

I show that organizational identities (and their change) influence the scope of what is deemed possible to discover, monitor, and experiment with and what is seen as necessary to be flexible and robust against. Organizational identities define how companies identify and treat uncertainties. The other finding of Essay 2 further proves this notion. The transformation of peripheral companies' domain identities serves as a deterrent to isomorphic changes within the industry and, by this, shapes other industry participants' uncertainty identification and treatment processes.

My findings from Essay 3 posit another example of uncertainty treatment interactions. First-mover technology investment strategies are driven by companies' desire to diversify to address uncertainties arising from new technologies and applications (see green arrows). When looking at diversification from an incumbent's perspective of "portfolio investing" in various emerging technologies, this process complements experimentation and vice versa, where experimentation leads to diversification (complementary interaction; follow green arrows from diversification). In turn, both depend on information obtained during "discovery, search and monitoring processes" (supportive). Interestingly, the search process and the following strategizing can lead to inflexibility (strategy inertia), which I identified as disadvantageous (competing; see green arrow to flexibility). How these uncertainty treatments create value (financial performance of diversification) depends on the timing strategy (creator, anticipator, follower) an incumbent is following. For example, my results show that firms following an anticipator approach can behave opportunistically (flexible in strategizing), following peers into technologies while reducing behavioral inconsistencies (leveraging experiences), which can partly shield companies from the drawback of missing trends in their earliest phase.

Additionally, Arend (2024b) described that creating scenarios can help clarify what factors a company needs to build robustness against, and monitoring shows where companies could most effectively experiment. Consequently, I argue that a framework is necessary for structuring the possible interaction modes of uncertainty treatment strategies in general and for uncertainties arising from emerging technologies in particular. For these, my dissertation lays the foundation to build upon. I identified supportive, complementary, and competing interaction methods. By recognizing organizational identities as influential in treatment strategies' applicability and success probability, I also established the cornerstone of integrating boundary conditions in the picture of uncertainty treatments.

Third, the literature emphasizes that there is no treatment for unknown unknowns (untreatable uncertainties) and that only luck leads to positive outcomes when confronted with these (Arend, 2024b). However, Essay 2 draws on the theory of serendipity and shows that the potential "contact area" with luck can be increased through preparation. I thus argue that companies can very well prepare for "black swan" events. Managerial action can increase resilience against shocks (see influence of Ukraine/Russia war on oil and gas profits in Essay 2) and lead to positive associations to transition (see Ørsted response to supply chain shocks). Consequently, treating these uncertainties does not involve uncovering unknown information or tweaking markets. However, it should focus much more on increasing the likelihood of "being lucky" and grasping black swan events as crystallization points to steer organizations.

Managerial Implications

My findings have implications for managers of firms facing emerging technologies' uncertainties and policymakers aiming to support the proliferation of certain technologies. Collectively, the essays and the derived framework for the uncertainty-treatment nexus facilitate cognitive processes that can inform management on how to tackle knowledge problems (Kapoor & Klueter, 2021). These help companies to answer where uncertainties arise and how to treat the identified uncertainties. In particular, my dissertation emphasizes the interactions and dependencies of uncertainties, technologies in technology fields, and treatment strategies for uncertainties. The same thinking is valid for policymakers; knowing which uncertainties exist for companies and how they aim to treat them should be the basis for designing incentive schemes and regulations to reduce these uncertainties effectively. Governments should thereby refrain from picking individual technologies as winners (Rosenberg, 1996) but should rather aim at the uncertainties arising from technology fields and overall trends, as shown in this dissertation, for the sustainability transition. Individually, the essays detail these evaluations.

Essay 1 offers a comprehensive scenario-driven perspective on the anticipated evolution of the hydrogen technology field by the year 2035, highlighting associated outcomes that diverge from demand-driven projections. Notably, it is cautious about hydrogen's widespread adoption in mobility applications. Its findings can foster transparency, facilitating a more precise research and investment strategy to expedite the availability of suitable green technologies for various applications, thereby averting investments in undesired technologies (Suurs & Hekkert, 2009). This insight is essential for political actors, as the transition to hydrogen presents both opportunities and challenges for national economies (Eicke & De Blasio, 2022; Noussan et al., 2021). Previous research anticipates that this transition will lead to new dependencies and market dynamics (Eicke & De Blasio, 2022; Noussan et al., 2021). In particular, previously energy-dependent economies might achieve energy autonomy or even ascend to become hydrogen exporters (Eicke & De Blasio, 2022; Noussan et al., 2021). Vice versa, high-consumption countries face the risk of deepening dependencies, setting the stage for new geopolitical tensions (Eicke & De Blasio, 2022; Noussan et al., 2021). To navigate the hydrogen transition effectively, it is essential for political actors to anticipate and prepare for upcoming changes. Thus, political actors could use both future scenarios as a basis for developing strategies to shape political measures, including subsidies, research funding, or tax incentives. It is necessary to remember that promoting a specific technical solution is also a decision against promoting its alternative.

Essay 2 guides how to manage transition journeys for companies' managements, policymakers, and investors. I find that management should proactively trial sustainable business models, broaden the organizational identity from product- to problem-focused narratives, and adjust pre-conditions to enhance serendipity. Through this, organizations can treat uncertainties arising from sustainable transitions. This includes viewing technology strategies as platforms for change rather than reasons for it, necessitating an exploratory mindset in early trialing different models and technologies. Careful investments are crucial, as illustrated by Shell's decision to prioritize carbon capture and storage (CCS) and biofuels over wind and solar in 2008. Gravitating towards technologies adjacent and connected to the traditionally used technologies can lead to lock-ins and challenges in long-term viability. I urge management to resist this temptation. Regarding institutional investors and policymakers, I find that they must recognize the sustainability transition as a vulnerable phase marked by heightened uncertainty, potentially necessitating actions that shield companies against takeovers and external influence. Equally, policymakers can reduce uncertainties by designing incentives to encourage active engagement with emerging technologies and sustainable business models. They can do so, for instance, by strategically introducing disruptive shocks like imposing carbon prices or product bans to stimulate an economic imperative for change. Consistency in these measures is vital to provide certainty, reinforce the decline in the traditional business's appeal, and prevent expectations of regulatory shifts favoring it.

From Essay 3, I deduce that managers should assume a first-mover advantage across their technology entries and pursue a portfolio entry timing strategy while being aware of the risks, especially of being strategy-inert when following early entry strategies. Uncertainty cannot always be reduced by gathering more information, as its value diminishes, and some information may be unknowable or outdated. Effective strategies focus on reducing non-technology uncertainties, such as maintaining consistency in sectors where new technologies are employed. These processes differ from those in core businesses, highlighting the need for separate decision-making, potentially through a corporate venture capital entity. Entry strategies should be adaptable, tailored to the level of uncertainty, and flexible enough to adjust to changing circumstances and new information.

Limitations and Future Research

Like all research endeavors, this dissertation is not exempt from limitations. Four key areas emerge as opportunities for future research to overcome these limitations. First, collectively, I call for more research on the interactions of uncertainties and their treatment strategies associated with emerging technologies. Researchers can use the shown framework to build upon. Additionally, since I showed that organizational identities influence treatment strategies, research on boundary conditions for these strategies needs more depth.

Second, while Delphi is a powerful method, I am also aware of its limitations, as the uncertainty of the future is not measurable and is not foreseeable. As Derbyshire (2017) highlights, subjective probabilities, as measured in the Delphi studies of Essay 1, are based on individual experiences and knowledge of experts and thus might not accurately reflect the actual uncertainty about the future, as each expert may have different perspectives and biases. Additionally, my newly developed solely on Delphi-data-grounded scenario approach needs validation. I argue that researchers could apply this technique in another setting where a multitude of competing and complementing technologies interplay, forming a broad technology field. These could include “artificial intelligence”, “human space exploration”, “personalized medicine”, and more. Lastly, some of the findings of Essay 1 are either controversial or could not reach a consensus while being perceived as highly relevant for the future of the hydrogen technology field. I am convinced further research on these questions is necessary.

Third, while Essay 2 offers valuable insights, the study focuses on European oil and gas companies and their transition processes. As a result, the findings may not capture the dynamics and factors at play, forming the relevant uncertainties in other geographies. Additionally, the sample is missing companies that may have attempted but canceled a transition process, which would be valuable for gauging how uncertainties influence transition failures. Although case studies based on interviews with industry experts and stakeholders yield valuable qualitative data, it is imperative to recognize the subjectivity and potential bias inherent in these data collection methods.

Fourth, Essay 3 uses VC firms as a proxy for incumbents’ technology entry decisions. Despite following other researchers (Lo et al., 2024; Makarevich & Kim, 2019) with this approach, the generalizability of the findings might be at risk. Further research is needed to validate my findings.

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Part B: Research Essays

Essay 1: The Field of Hydrogen Technologies in 2035
Insights from an Extended Delphi Approach

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

Keywords: Technology Foresight; Future of Hydrogen Technology; Delphi-based scenarios; Technology Field; Sustainability Transition; Real-Time Delphi

Introduction

Global warming has accelerated, and its impacts have become more hazardous and visible in recent years. To prevent substantial and irreversible changes to our ecosystems, a switch from fossil-fuel-based economies to systems run on renewable energies is needed (IPCC, 2022). One pathway for defossilization can be via hydrogen as an energy vector (Wang et al., 2021), which is perceived as being at the brink of a significant global demand scale-up, potentially resulting in a medium-term supply scarcity (Wappler et al., 2022). Already today, the world produces 100 megatons (Mt) of mainly "grey" hydrogen (made from fossil sources) and is prognosed to reach 500 Mt by 2050, then primarily stemming from "green" hydrogen (H_2 produced with electrolyzers from green electricity) (The Economist, 2021).

Hydrogen can be applied across a broad set of applications in both easy and hard-to-abate use-cases (applications or situations where technology can solve an engineering problem). Nowadays, consumption is mainly driven by its use as a feedstock element, e.g., in fertilizer production and the oil and gas value chain. In contrast, the prognosed five-fold increase in consumption derives from applications where hydrogen(-derivatives) would substitute fossil fuels such as heating, transportation fuel, industrial energy, grid balancing, and more (The Economist, 2021). Until 2050, the annual growth rate is forecasted to be highest in the intermediate years of 2030 to 2040, following an S-curve uptake. In this period, hydrogen is prognosed to start venturing into these "new" applications (Hydrogen Council, 2021).

But most hydrogen-based technologies are not yet market-ready on a global scale, and paired with a green hydrogen supply scarcity, it is still unknown in which applications hydrogen-based technologies will become dominant. The most essential preconditions for all hydrogen-based technologies are an increase in technological readiness and a reduction of costs, next to the decline of costs for renewable electricity as the core input factor (Gül et al., 2019; IEA, 2022; The Economist, 2021). Many of these problems originate from a lack of scale, missing investments, incomplete standards, and missing infrastructures (Ren et al., 2020). Hence, the phase-in into new applications – outside today's use – marks a milestone in every projection on how hydrogen might scale up (Oliveira et al., 2021).

Bringing hydrogen technologies to market readiness is costly and thus frequently requires subsidization. In 2019, 35 out of 50 government support programs for H_2-applications were focused on passenger cars, refueling stations, and city buses. This incentivization scheme seems systemic in all 19 national hydrogen strategies reviewed (Gül et al., 2019). However, it is often doubted whether H_2 will become prevalent in these applications; experts reckon they might be better defossilized with non-hydrogen-based technologies, i.e., battery-electric

(Liebreich, 2021). Considering that transforming the industry will consume up to USD 150bn by 2030, it is important to promote effective investment decisions (The Economist, 2021). Thus, actors (e.g., policy and corporate decision-makers) need more clarity and transparency where the use of green hydrogen is most likely.

In recent years, several studies have focused on hydrogen, aiming to create the needed transparency. However, many of these studies have in common that they either focus on single technologies (CIFS, 2021; Lee et al., 2022; Thoennes & Busse, 2014), analyze hydrogen impacts independent from the underlying technologies (Chen & Hsu, 2019), or are geographically narrowly focused (Li et al., 2021). Next to these - mainly qualitative - studies, there are "techno-economic" simulations focused on forecasting overall global hydrogen demands while disregarding technological details (Hydrogen Council, 2020; IEA, 2021b; Wappler et al., 2022). Hence, no identified study answered questions about the technology mix needed to support the hydrogen transition, especially during the period from 2030-2040.

Hydrogen and its enabling technologies must be seen as a holistic field of interdepending enabling technologies rather than a disjunct set (Unruh, 2000). These technologies include electrolyzers, fuel cells, liquid hydrogen shipping, synfuels, turbine technology for hydrogen, and many more. Being dependent on the parallel proliferation of such a diverse set of technologies makes hydrogen, like other sustainable technology fields, unique. Especially in the context of sustainability technologies, there is a great need "to move beyond single innovations" and towards "complementary interactions between emerging and existing technologies" (Köhler et al., 2019). Sandén & Hillman (2011) introduced this view and described six possible modes of inter-technology interactions, clearly stating that in the wake of transitions, competing and complementary technologies cannot be viewed separately. Hydrogen's "foreseen" success is often linked to its widespread use across different industries, leveraging symbiotic benefits from interconnected technologies, e.g., via sector coupling or bundling of demands (Abdin et al., 2020). Hence, hydrogen's system-level success depends not on the proliferation of a few single technologies but on the evolution of the technology field (Markard & Hoffmann, 2016). For the remaining paper, I frame interrelated technologies as the "hydrogen technology field", using a term coined by patent research (Schankerman, 1998). Summarizing this, I answer the following questions: 1) How will the technology field of hydrogen develop until 2035? and 2) How to efficiently create future scenarios in the context of highly interdependent technology fields?

I developed an extension to the Delphi method, allowing me to forecast the development of technology fields and create consistent future scenarios without a traditional multi-method approach. Additionally, I provide an up-to-date holistic scenario-driven view on the future development of the technology field of hydrogen in various use-cases along the entire value chain. I thereby focus on the technology mix constituting the hydrogen economy in 2035 while refraining from hydrogen volume forecasting. I do this via two interconnected, staged Delphi studies (further called phases): One focused solely on technological dominance and hindrance reasons, while the other one addresses the related consequences. I ran both phases in 2022 aiming to create foresight for the 2035. My unique scenario-creation approach relies only on data of "voting behavior" acquired from the Delphi phases and clusters of like-minded experts with a similar set of underlying assumptions about the development of the hydrogen technology field in groups. These assumptions were measured indirectly via preferences for technological dominance during the first phase.

With my research, I contribute methodologically to technology foresight and generate insights about the future of the hydrogen economy. Firstly, I enhanced the Delphi method to efficiently create forecasts and create consistent scenarios for entire technology fields. Furthermore, my two-stage approach enables an ex-post analysis of why and how the presented scenarios might turn out to be incorrect by dissecting technological dominances, hindrance reasons, and technology consequences. Secondly, I contribute to sustainability research. This paper presents an up-to-date holistic scenario-driven view on the future development of the technology field of hydrogen in the year 2035 and the associated consequences, which are partly misaligned with demand-driven forecasts. It is significantly more skeptical of hydrogen proliferation in mobility applications. The transparency I create with this effort will allow a more targeted research and investment approach for bringing the right green technologies for the right use-case to mass market availability to prevent investments in undesired technologies (Suurs & Hekkert, 2009).

The article is structured as follows. First, I elaborate on the backgrounds in technology foresight generally and within the field of hydrogen specifically. The following section explains my novel two-staged approach to the Delphi method, while the sections on "Technological Dominances" and "Technological Consequences" explain the method and results for the two Delphi phases separately. I split the method and results section along the two study phases to ease readers' understanding. The "Scenario Development" section brings the results from the two phases together and explains my new, unique approach to clustering experts and scenario creation in detail. The last section concludes and discusses implications for companies, policymakers, and academic research.

Background

Past hydrogen forecast activity

Hydrogen has been a subject of technological foresight for multiple decades (Stevenson, 2010; Valette et al., 1978). It already went through three previous hype cycles, the first in the 70s induced by the global oil price shock, the second in the 90s when having climate concerns became popular among parts of the population, and the third in the 2000s during the rising oil prices and when the discussion about "peak oil" took place. In all cases, enthusiasm about hydrogen dipped back to low interest when underlying "trends" became less prominent or oil prices normalized (Gül et al., 2019). Generally, these phases of high interest in hydrogen were accompanied by extensive forecasting activity, summarized by McDowall & Eames (2006). In more recent years, a comparison of uptake scenarios was compiled by Stevenson (2010) and Wappler et al. (2022).

Many past forecasts for the uptake of hydrogen usage in the global economy were overly optimistic. A prominent example is the EU's forecast of a 5% hydrogen share in passenger cars by 2020, which it failed to achieve (Demirbas, 2017). At the same time, other sustainable technologies such as batteries and solar even overshot their learning rate forecasts, leading to a more substantial cost decline and higher market uptake compared to fuel cell solutions (Hellstern et al., 2021).

I think this could partially derive from missing to integrate the concept of interrelated technologies into future forecasts – both competing (e.g., fuel cell vs. battery-electric drive trains) and complementary ones (e.g., fuel cells and liquified hydrogen storage) (Sandén & Hillman, 2011). Related to this, I argue a forecast in the field of sustainability technologies should also incorporate the concepts of path dependencies and technological infliction points in the analysis of entire technology fields. For example, an analysis run by the industry association "Hydrogen Council" ranked in which year hydrogen-based technologies will become cost-competitive against the currently dominant technology and the best green alternative based on assumed learning rates on the total cost of ownership (Hydrogen Council, 2020). This approach neglects the aforementioned concepts. If, for instance, electric heat pumps (run with renewable electricity) became widely adopted for private housing heating, buildings might be cut off or never connected to the gas grid. Even a hypothetical future cost advantage would generate no technological dominance for hydrogen boilers. In this example, the faster time-to-market of heat pumps marks the infliction point, which leads to lock-in on direct electricity use due to the change in underlying infrastructure. Indeed, in many other use-cases, the discussion also comes down to hydrogen-based vs. direct-electricity-use technologies (Ball

& Weeda, 2015; Marchenko & Solomin, 2015). Especially since hydrogen is at first a defossilization problem itself (replacement of 100 megatons “grey” hydrogen) and only second a defossilization lever for other sectors, the efficient use (e.g., cost-efficiency, max. defossilization effect) must be limited to the “right” applications (The Economist, 2021). Thus, to analyze the future of the hydrogen technology field, a method able to forecast highly complex and interdependent situations is needed.

The Delphi method

The understanding of the term technology foresight differs (Porter, 2010). In this paper, I consider that the aim of technological forecasting – especially for new and emerging technologies – is to draw future scenarios and identify influence factors or trends (Gausemeier et al., 1998). By reducing future uncertainty, forecasting creates a basis for decision-making across different stakeholder levels (individuals, businesses, industries, ecosystems, politics, and so on) (Powell, 1992). However, forecasting can never be entirely precise; it merely tries to anticipate the most likely future outcomes (Saritas & Oner, 2004).

In order to achieve these goals, various techniques can be classified into three categories: exploratory, normative, and a combination of the aforementioned (Cho & Daim, 2013; Roberts, 1969; “Technology Futures Analysis”, 2004). This type of grouping is only one approach; the literature also knows other frameworks for clustering the forecasting methods (Roper, 2011). Exploratory techniques are the projection of the future based on current technology trends extrapolated with assumed progress rates (e.g., S-curves, bibliometric analysis), for instance, the hydrogen demand forecasts mentioned earlier (The Economist, 2021). In comparison, normative approaches asses the path necessary to reach a certain future outcome and the associated probability of occurrence (e.g., multi-criteria analysis, backcasting). Lastly, exploratory/normative combinations are a mix of the two categories described, including – among others – Delphi studies, nominal group techniques, and trend impact analysis.

Delphi has become a standard tool in foresight research and is also used in engineering and technology settings (Flostrand et al., 2020). It is often the only method to run large-scale national or industry-wide forecasts with a broad set of stakeholders (Martino, 2003). Developed in the 1960s by the RAND project, Delphi studies are often described as structured, systematic, and interactive expert panel-based forecasting techniques. Initially, the primary focus was creating consensus about specific questions among experts (Dalkey & Helmer, 1963). Today, it is widely used to derive opinions from and discuss them among experts (Landeta, 2006). Methodologically, Delphi studies rely on the evaluation of concise and clear projections, which experts evaluate in various survey rounds or – in more recent years – which are “live” supported by online platforms (known as RT or Real-Time Delphi's) (Gordon & Pease, 2006; von der Gracht & Darkow, 2010). The format aims to decrease common issues of round-based formats, like high dropout rates, low interaction, low engagement, and long study duration with high moderator effort (Gnatzy et al., 2011). It has recently been applied for forecasting additive manufacturing (Jiang et al., 2017) and exploring the impact of COVID-19 on the European football ecosystem (Beiderbeck et al., 2021b).

The Delphi method is well suited to integrate the complex interdependencies arising from forecasting technology fields but was, as of my knowledge, never used for this. Due to its expert-based format, it can capture multifaceted problems decision-makers are thinking about (Daim et al., 2013), has great legitimacy for creating foresight in severely complex settings (Donohoe & Needham, 2009), and is well-suited for topics where future perspectives are incomplete, and debate is still ongoing (Fink-Hafner et al., 2019; J. Skulmoski et al., 2007). It can be methodologically adapted, features the advantages of combining qualitative and quantitative research (Donohoe & Needham, 2009), and can be combined with scenario approaches (Nowack et al., 2011).

In my opinion, current approaches to form scenarios from the Delphi results fall short of identifying underlying key drivers by often relying on clustering projections with similar probability and impact into groups (e.g., compare Beiderbeck et al., 2021b). For example, Culot et al. (2020) used the Delphi method to broadly describe the phenomena of "Industry 4.0" and map out future scenarios but missed incorporating underlying enabling technologies.

Existing Delphi-enabled research on the future of hydrogen as an energy vector

Multiple Delphi studies have been conducted on these topics in the past. A review of them was conducted by Stevenson (2010). Table B-2 is based on this work but was extended for the time after 2010. Most of the Delphi studies focus on isolated technologies (CIFS, 2021; Lee et al., 2022; Thoennes & Busse, 2014), analyze hydrogen impacts independent from the underlying technologies (Chen & Hsu, 2019), are geographically narrowly focused (Li et al., 2021), ignore hindrance reasons (Joergensen et al., 2004) or are outdated (Valette et al., 1978). In short, there is a need for a new study on the future of hydrogen to resolve the above-mentioned tensions. Most importantly, creating a holistic technology-field view of relevant use-cases across the entire hydrogen value chain (production, storage, transport, and consumption) is necessary. Furthermore, the study must incorporate multiple perspectives (PEST framework), hindrance reasons for, and dependencies between technologies in adjacent use-cases and should analyze the critical time horizons for the H_2- ecosystem, i.e., 2035.

Year of publication	Forecast Period	Location Focus	Topic Focus	Source
1978	1985 – 2000	Global	Production and consumption breakdown	(Valette et al., 1978)
2004	2020-2030	Europe	Production and consumption use-cases	(Joergensen et al., 2004)
2005	No time focus	Taiwan	Consumption in mobility applications	(Tzeng et al., 2005)
2007	No time focus	Unspecified	Discovering divergent options in H2 production	(Yüzügüllü & Deason, 2007)
2008	2050	UK	Passenger transport	(Bristow et al., 2008)
2009	2019-2024	Global	Hindrance reasons for fuel cell uptake	(Hart et al., 2009)
2011	No time focus	n/a	Hydrogen production	(Chang et al., 2011)
2012	2020-2050	Global	H_2 contribution to global energy demand	(Stevenson, 2012)
2014	2030	Global	Performance parameters for automotive fuel cells	(Thoennes & Busse, 2014)
2019	Varying per projection	Taiwan	Hydrogen ecosystem	(Chen & Hsu, 2019)
2021	Varying per projection	China	Hydrogen ecosystem	(Li et al., 2021)
2021	2040	Global	Hindrance reasons and drivers for FC uptake	(CIFS, 2021)
2022	n/a	South Korea	Hydrogen fuel cell power generation	(Lee et al., 2022)

Table B-2: Overview of hydrogen-associated Delphi studies in academic research (based on V. Stevenson, 2010)

Approach of Delphi Study

Study conceptualization

To run a valid Delphi study on the future of hydrogen as a technology field, I started with desk research, exploratory interviews, and a workshop to develop a framework addressing my research goal (Beiderbeck et al., 2021b). I then decided to use a Real-Time Delphi and base my approach on a procedure established by Roßmann et al. (2018) (see Figure B-3). The study was run using the software Surveylet by Calibrum. By doing so, I followed methodological recommendations (Aengenheyster et al., 2017; Beiderbeck et al., 2021a). This setup enabled me to allow experts to start, pause, continue, and even switch devices during their work on the survey. As for the time horizon, I decided to use a fixed-horizon approach to 2035, which is right in the middle of the predicted hydrogen transition. Thus, as outlined before, it is particularly important for the ramp-up of a hydrogen ecosystem (Gül et al., 2019). At the same time, the lower visibility (most studies look at periods before or after) makes this time horizon interesting for scientific and practical considerations.

To tackle the aforementioned challenges in the forecasting of technology fields, I decided to run two Delphi studies in sequence but interconnected to dissect technological dominances from their consequences and enable an overarching cluster analysis (see Figure B-4). The first phase focused on the emergence of hydrogen-based solutions in selected use-cases along the hydrogen value chain. I asked participants to assess which technological solution (e.g., fuel cell, battery electric, internal combustion engine) would dominate a specific use-case (e.g., passenger vehicles) in the year 2035, what (political, economic, societal, technological) hindrance reasons might exist, and whether the technology would benefit from any path dependencies (self-reinforcing mechanisms on technological, institutional and organizational level) during scale up. This phase was run between May and June 2022, which is why I controlled expert answers for the impact of the Ukraine/Russia conflict (also in Phase 2). On average, experts believed the influence to be neutral (2.9 on a "1-5"-point Likert scale with a 0.85 standard deviation), which shows that the recent conflict did not influence the results of my study. Further analysis of this factor was thus neglected. After Phase 1, I ran an intermediate analysis (incl. descriptive statistics), which I shared with the experts. The aim was to motivate experts to participate in Phase 2 (Kawamoto et al., 2019). I sent out the report two weeks after the end of Phase 1.

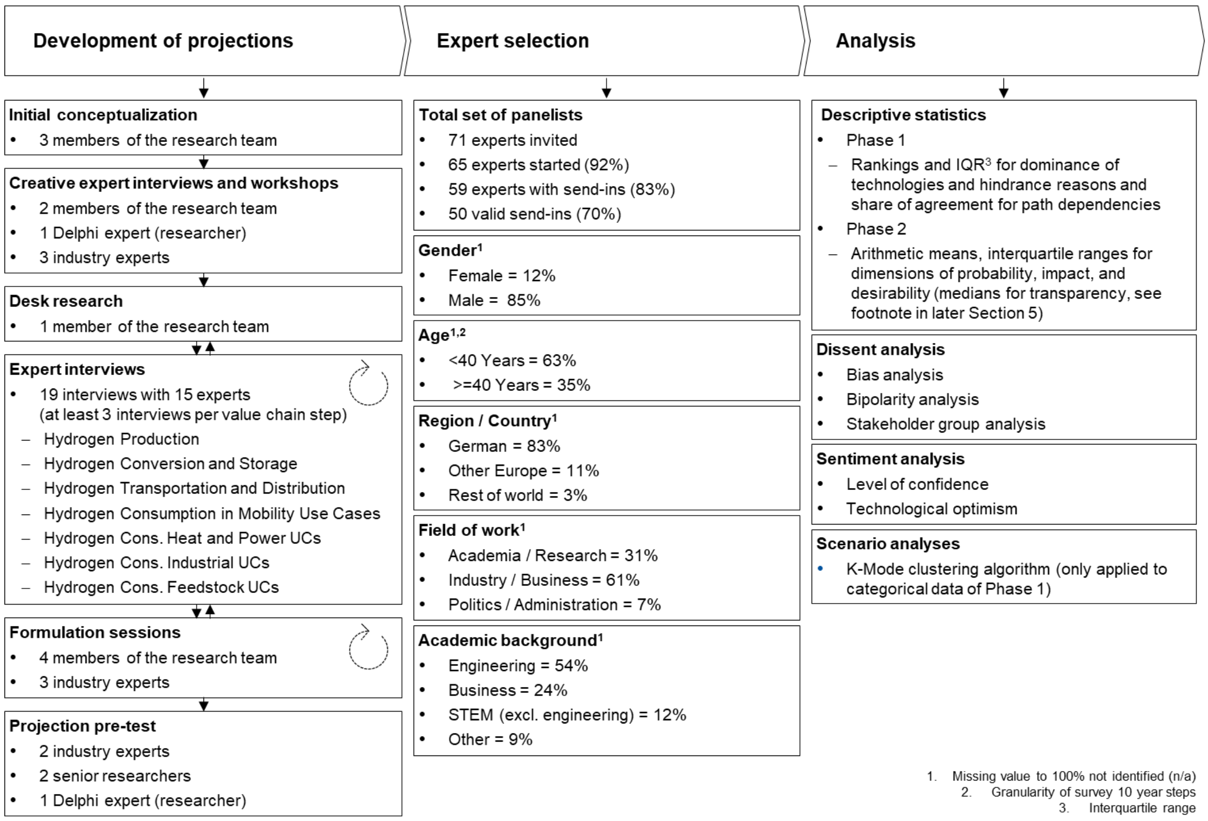

Figure B-3: Process for development of projections, expert selection, and analysis (based on Beiderbeck et al., 2021b; Roßmann et al., 2018)

During Phase 2, the panel was asked to evaluate projections focusing on preconditions for and impacts from the picture drawn in Phase 1. Here, experts were asked to rate the expected probabilities of occurrence, the firm impact, and the subjective desirability for future projections. Additionally, experts rated follow-up questions on technological interdependencies between use-cases from Phase 1. This phase was online between July and August 2022. Afterward, I ran a standard descriptive analysis (means, rankings, consensus) complemented by a dissent and sentiment analysis as proposed by recent literature (Beiderbeck et al., 2021a).

Finally, I brought my results from the two interconnected study phases together by creating two distinct scenarios on how the future of hydrogen might evolve.

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

Figure B-4: Conceptual overview of the Delphi study approach

Selection of the expert panel

As in all Delphi studies, selecting the expert panel is a key component to ensuring the validity of results (Hasson et al., 2000). Following the literature, I selected a diverse set of experts from various backgrounds, geographical regions, academic fields, and age groups (Beiderbeck et al., 2021a). The experts were found through multiple sources: 1) From a cross-sectorial research cluster, 2) via online business networks, 3) acquired offline via a hydrogen industry convention, and 4) from the network of the researchers and pyramiding. All experts were invited individually after a background check by the researchers. There are different recommendations on the size of Delphi panels. Due to the breadth of my study, I settled down on a target of 40-60 experts, equivalent to other recent technology-focused Delphi studies (Jiang et al., 2017). I focused on acquiring a distributed group of experts from the different value chain categories to guarantee the validity of answers in each subsection of my survey.

During Phase 1, 65 participants started the survey, 59 made send-ins, and 50 were valid (overview of panels' demographics in Figure B-3), of whom 36 also made valid send-ins in Phase 2. In Phase 1, the experts logged in, adjusted on average 2.84 times, and spent 27 minutes per session. In Phase 2, they logged in on average three times and spent 20 minutes. This sums up to ~100 hours of combined efforts. We know that our participation rates are comparatively high, which we attribute to rigorously following up with experts upon their participation. We sent out weekly participation and reevaluation reminders.

Technological Dominance (Phase 1)

Research methodology

<u>Development of projections</u>

For Phase 1, I followed an analytical approach to select possible applications for hydrogen and alternative technical solutions. First, I aggregated 49 potential use-cases for hydrogen from databases and reports of the International Energy Agency (IEA Hydrogen tracking report from Nov. 2021 and ETP Clean Energy Technology Guide) and reports issued by the Hydrogen Council (Hydrogen Council, 2020; IEA, 2021b, 2022). From the same source, I derived potential technical solutions for all potential use-cases. To further enhance the set of technologies, I ran extensive desk research and interviewed 18 industry and academic experts. In the next step, I clustered the use-cases in domains and categories along the value chain steps of the hydrogen economy. I then started short-listing these use-cases to guarantee a survey length that experts can answer comprehensively in an acceptable time frame. For the selection, I followed a 4-step logic to shortlist 19 use-cases (see Table B-3). The logic was designed among the researchers and tested with two industry experts (see Appendix B-1). During the Delphi, the participants were asked to rank the technologies for the use-cases with a declining probability of becoming dominant by 2035. On average, I provided the experts with 7.5 technological solutions for each use-case. Both the use-cases and the selected technological solutions were then cross-checked with the interviewees.

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

Table B-3: Overview of domains, categories, and use-cases

Implementation of Phase 1

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

Descriptive statistics

I ranked the technologies per use-case according to their average, assigned rank, and excluded technologies for which less than 10% of experts voted to remove outliers. I then calculated the consensus for the top-ranked technology via interquartile ranges, which is standard in Delphi literature. A consensus was reached when the interquartile range (IQR) was smaller than 25% of the selection range (Beiderbeck et al., 2021a). For the questions on hindrance reasons and the existence of path dependencies, standard descriptive statistics such as average and median selections of experts were calculated. Lastly, I coded the written feedback to allow quantitative analysis on top of qualitative insights from selected comments. I followed an open (inductive) coding approach and created categories by cross-comparing the generated codes (see Appendix B-2 for the abbreviated coding table).

Dissent and sentiment analysis

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

Results

Descriptive statistics

Table B-4 shows the results of Phase 1. In total, a consensus was reached on 13 out of the 19 projections (ca. 70%), indicating a high degree of agreement among experts. Depicting these results per technology domain, however, paints a different picture: For use-cases in the domain "supply", a consensus could only be reached on 2 out of 6 projections (33%), whereas in the domain "consumption" 11 out of 13 projections (84%) reached consensus. The results suggest that the perspective on where to use and not to use hydrogen-based technologies in consumption is much clearer than the view on which set of technologies will compile the production, transportation, and distribution of the required hydrogen.

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

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

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

Table B-4: Descriptive statistics for Phase 1

Path dependencies play a major role in technological dominance constructively and obstructively (Klitkou et al., 2015). Generally, these can be clustered in technological (economies of scale and scope, network externalities, learning) and institutional (expectations and expectations of expectations, coordination effects, complementary effects) path dependencies (Sydow & Schreyögg, 2005). In my study, the (by experts) perceived path dependency of the highest ranked technology can give hints on where hydrogen-based technologies will prevail once a critical mass of "users/consumers" is reached due to lock-ins (e.g., from infrastructure build-ups, economies of scale, etc.,) and where hydrogen-based solutions might remain insignificant due to lock-ins on other (ideally) green alternatives even if hydrogen-based technologies might become cost-competitive.

One example are passenger vehicles: Experts believe building up a second infrastructure next to charging stations for BEVs (battery electric vehicles) is prohibitively expensive to build and run. Hence, the critical infliction point for "market readiness" was missed for FCEVs (fuel cell electric vehicles). For instance, one expert let me know: "BEV will be dominating everywhere [road-based transport]; it is cheaper, more mature, and in the mainstream strategy of OEMs (original equipment manufacturers)". The path dependencies are perceived the highest on average (77%) in the category of "consumption in transportation", where at the same time, most use-cases are perceived to be dominated by non-hydrogen-based solutions. The only exception is the case of heavy-duty trucks, where hydrogen is believed to be dominant and has a high path dependency (80% of experts see dependency). For the domain of "(hydrogen) supply", high path dependencies are seen, especially in the transportation of hydrogen use-cases "Long distance transport" and "Regional distribution", where infrastructure needs to be built up. Perceived path dependencies are, on average (49%), the lowest in industrial heat and power and feedstock application, where already today, not only one technology dominates the described use-cases, but different solutions co-exist.

I can mirror these results in the analysis of experts' comments. In total, I received 448 comments (on average 28 words long), which were coded to allow reflection about pro and con arguments for hydrogen technologies and experts' beliefs about the type of dominance technologies in the specific use-cases can achieve. I found that the strongest arguments for hydrogen usage were "the ability to reuse assets / tech / infrastructure", "flexibility", "social acceptance", "energy autarky", and "ability for sector coupling" (order in declining mentioning rate). The opposing factors were "existing or emerging lock-in on other (green) technologies", "missing regulatory support", "missing availability of products (cars, trucks, ships)", "low overall efficiency", and "the need to use rare hydrogen in use-cases where no other abatement technology is feasible". Interestingly, many of the received pro arguments can be placed on a socio-economic level (autarky, seasonal energy storage, sector coupling, etc.). At the same time, opposing factors are often situated on the use-case or application level (efficiency, market readiness, product availability, costs, etc.). Furthermore, all comments mention the dependence of green hydrogen on the availability of renewable electricity. Experts also gave insights into the type of dominance. I found that 60% of the comments suggested a single dominance of one technology in the specific use-cases due to lock-ins from infrastructure, investments, and economies of scale. However, the picture changes when depicting the results for domains only: In "supply", 63% of comments indicated the co-existence of various technologies, while in transportation, 78% suggested a sole technology to be dominant.

Dissent and sentiment analysis

In the stakeholder group analysis (split by activity in value chain steps), I found group differences are slight but distinct in selected projections. In these cases, the actual category experts (e.g., transportation experts for transportation use-cases) are always more skeptical regarding green technologies' dominance in their field than "adjacent" experts. I saw robust results for use-cases in the domain "supply", indicating that experts from various value chain backgrounds see the production and distribution of hydrogen the same way. The only slight difference occurred in "Long-term storage", where experts with a background in mobility applications ranked storage in the form of hydrocarbons higher than in the form of ammonia. This picture is coherent since many transportation applications would rely on hydrogen in the form of hydrocarbons (e.g., synfuels). In the use-cases in the category "Consumption – Transportation", again, the first ranks are robust and in the majority depending on the stakeholder group.

However, for heavy-duty trucks, "supply" experts believe in BEVs (battery electric vehicles) as the best alternative. In contrast, the specific category experts (Consumption – Transportation) argue that combustion engines run on diesel, and experts from the background of heat and power think biofuels are the next best alternative. Similar is valid for medium-haul aviation, where heat and power experts believe stronger that turbines run on mixtures of kerosine and syn-/biofuels. In "Short-haul aviation", experts from transportation as well as heat and power see battery-driven flight as dominant, whereas hydrogen production experts believe in turbines run on mixtures (kerosine, bio-/synfuels). The most considerable divergence can be seen in high-grade industrial heat, where "supply" experts argue for hydrogen burners, transportation experts believe in biogas burners, and people from the heat and power segment think natural gas will still dominate. Similar holds for CHP (combined heat and power), where both transportation and supply experts believe in hydrogen turbines' dominance. In contrast, experts with heat and power backgrounds are prone to choose fossil-powered steam turbines.

Looking into sentiment analysis – through analysis of experts' level of confidence (LoC) – I can show that experts also translate their expertise (based on technologies in their field) to technological solutions in other fields and are again more skeptical within these. I correlated the average rank for each technology per use-case with the three distinct LoCs per category. I could not find any technology-LoC-combination with p-values below 0.01. However, three are significant at $p < 0.05$. First, LoC in the production of hydrogen correlates negatively with the rank of grey hydrogen as a means of hydrogen production. This indicates that experts confident in hydrogen production believe stronger in the viability of grey hydrogen as being dominant in 2035. Second, experts with high LoC in hydrogen production tend to rank internal combustion engines (biofuels) higher than those experts with low confidence. Third, experts with high expertise in transportation believe less in the dominance of fuel cells for CHP applications.

Lastly, I calculated regressions on the average rank for each technology per use-case with the experts' overall "Technological Openness". I found significance at $p < 0.05$ for two correlations, fuel cell driven medium-haul aviation with compressed hydrogen (even significant at $p < 0.01$) and hydrogen fuel cells in CHP plants. Both show a lower ranking with increasing tech openness for the two respective technologies. Both tech solutions are at a low technological readiness level in their specific use-case, showing that even with higher technological openness, experts do not become "naïve" to believe in technological feasibility until 2035.

Technological Consequences (Phase 2)

Research methodology

Development of projections

For Phase 2, I relied on multiple sources to create the projections, following other studies' approaches (Jiang et al., 2017). To create the projections, I interviewed at least two experts per use-case category (in total 15 experts) in a semi-structured format along the "PEST"-framework (political, economic, social, technological) (Beiderbeck et al., 2021a). Additionally, I conducted a workshop among the researchers and applied desk research. Furthermore, I was able to leverage the comments from Phase 1 to create additional projections. In total, I identified 120 projections. To shortlist, I eliminated those projections directly connected to use-cases excluded during the Phase 1 shortlisting. Then, I further shortened the list in joint sessions with selected experts from the different categories of the value chain. In the last step, I selected those projections connected to topics and comments from the results of Phase 1 by creating an interdependency matrix of projections and technologies (see Appendix B-3), leading to a set of

23 projections. Those I refined in formulation sessions with experts and researchers (Hasson & Keeney, 2011). This iterative process ensured methodological correctness (Landeta, 2006).

Implementation of Phase 2

During Phase 2, I followed the same survey structure as in Phase 1, with the sole difference that there was a group of "general" questions that each expert was requested to answer (skipping of individual questions possible), indifferently from his or her background and topic selection. In the questionnaire, the experts were then asked to rate 19 (out of 23) projections on their expected probability, firm impact, and subjective desirability towards 2035. For "probability", experts could choose between 0% and 100% in intervals of 10%p. For the dimensions "impact" and "desirability", I used 5-point Likert scales (see Table B-5). The four other projections followed a different scheme. Three were projections where experts were asked to rank pre-defined answers, and one focused on evaluating cross-effects between technologies. The latter asked experts to rate the influence of technological developments in fuel cell technology for heavy-duty trucks on other mobility-related use-cases.

Descriptive statistics

I calculated consensus via interquartile ranges on the probability dimension. For the dimensions of impact and desirability, I calculated the averages and medians of the respective expert groups. Since the probability was answered via selecting from blocks of 10%, I used the upper and lower range average values to calculate the overall expert average. The few ranking questions in Phase 2 were treated like in Phase 1. Again, I coded the written feedback to allow quantitative analysis subsequent to qualitative insights.

Dissent and sentiment analysis

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

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

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

Table B-5: Overview of projections from Phase 2

Results

Descriptive statistics

Table B-6 shows that 9 of 19 (47%) projections reached a consensus (on probability), indicating that many questions around technology consequences are still debated.

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

(* indicates projections where consensus was reached, 1: Consensus for IQR<=8*0.25 in %, 2: Consensus for IQR<=5*0.25, 3: not probability but 5-Likert from 1 = significantly increase to 5 = significantly decrease, 4: Consensus for IQR<=3*0.25, P, I, D = Probability, Impact, Desirability)

Table B-6: Descriptive statistics for Phase 2

Additionally, 8 of 19 (42%) show a probability between 45% and 55%, showing that debate is still open and the likelihood of occurrence is a mere chance. The questions around hydrogen consumption in transportation show the lowest average probability (38%), whereas consumption in heat / power / industry / feedstock has the highest probability (54%). On average, the dimension "impact" is considered to have a "moderate" or "major" impact, which shows that the set of projections is relevant.

Since fuel cell electric vehicles (FCEV) heavy-duty trucks (HDT) were the single technology-"use-case" combination where a hydrogen-based solution was perceived as becoming dominant by 2035 in Phase 1, the projection on technological interdependencies of HDTs aimed to answer the question where possible positive spill-over effects from the application of FCEV in HDT might occur to other use-cases, Table B-7 shows the results. There is a high interdependence between HDTs and intercity, as well as city buses and medium-duty trucks. On the other hand, all other use-cases (passenger vehicles, ferries, river vessels, construction vehicles, and trains) are perceived as having minor chances to profit.

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

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

Table B-7: Descriptive statistics for technological interdependencies of Phase 2

Dissent and sentiment analysis

Analyzing the desirability bias, I found that 16 out of 19 projections showed a positive slope, but only in one projection the positive slope was significant, at a 99% level ($p < 0.01$). The affected projection (efficiency vs. technology) suffered from a mean deviation of MD=1.46. I calculated adjusted probability values for this projection along the method of Ecken et al. (2011) and found that even with adjusted probability values, the consensus (in this case, missing consensus) did not shift. Based on that, I decided not to control for a desirability bias.

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

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

The phenomenon of experts being more skeptical of their own segment of the value chain also holds in the confidence level analysis. For the projections of Phase 2, I calculated regressions between probability and level of confidence. None of the projections correlated at a 99% significance level ($p < 0.01$), but three projections were close to or below the 95%-level ($p < 0.05$). For the projection "Decentral or Central H_2", I found a positive correlation between LoC-supply and probability at $p = 0.03$, indicating that experts' confident in hydrogen production and distribution believe stronger in decentral production of H_2 than experts less confident in this field. For the projection "Replacing OPEC (Organization of Petroleum Exporting Countries)", I found a negative correlation between LoC-transportation and probability at $p = 0.05$. This implies that experts with high confidence in H_2 transportation applications expect a lower probability that a new "Hydrogen-OPEC" will be established by

2035. Lastly, I found a negative correlation between LoC-Heat/Power/Industry/Feedstock and the probability for the projection of "Startup innovation". This shows that experts confident in the heat and power segment believe the most substantial innovation to come from today's incumbents rather than new companies. This might derive from the fact that companies in this part (heat and power) of the value chain historically faced only a low number of disruptors (Żbikowski & Antosiuk, 2021). Overall, I can see a negative correlation of LoC-total (averaged across fields) to probability (only at $p = 0.15$), indicating that experts typically rank probability lower when their confidence is high.

In the last step, I calculated regressions between the average technological openness with the probability for each projection. I found seven projections with correlations significant at $p < 0.1$, of which three (Technology Openness, Market consolidation, Green H_2 certification) were significant at $p < 0.05$. For all of those, I found a negative correlation, meaning experts rate the probability higher when tech openness is low. This means tech-open experts believe stronger in a regulation that is not technologically open, think that market consolidation among FC and electrolyzer producers is less likely, and rate probability lower that a market for green H_2 certification will evolve. Overall, experts with a low technology openness tend to rate projections as more likely to occur at $p = 0.08$.

Scenario Development

Research methodology

Most Delphi studies resort to clustering the average results of the different collected data on two or more dimensions (e.g., probability vs. impact vs. desirability) (Beiderbeck et al., 2021b). This clustering can be conducted in multiple manners: manually based on visual analysis or by clustering algorithms, often reducing average Euclidian distances between projections (Beiderbeck et al., 2021a). However, these methods only state which projections received "similar" results and thus might not form inherently consistent scenarios (Nowack et al., 2011). Multiple approaches in the literature try to mitigate this fact. Many rely on mixed methods, i.e., combining the Delphi method with, for example, cross-impact analysis or scenario-planning. Often, combining these approaches results in a high level of complexity both during the set-up of the study and during the data aggregation (Bañuls & Turoff, 2011; Nowack et al., 2011). Researchers can, therefore, resort to narrowing the topic by reducing the number of projection forecasts or evaluating cross-impacts with experts individually in a workshop format, thus reducing the number of experts giving input (Bañuls & Turoff, 2011). Hence, I propose a lean approach to create consistent scenarios for entire technology fields.

The target of this approach was to create an explorative ("What can happen") scenario that incorporates the entire possible range of future scenarios (Nowack et al., 2011). Narrowly focused Delphi scenario approaches rely on analyzing and identifying all possible influencing factors and distinguishing scenarios along them (Al-Saleh, 2009). However, this approach cannot be applied to entire technology fields since an exhaustive identification of all factors cannot be done efficiently. For me, the scenario differentiation along experts' underlying and unstated beliefs about future trends seemed most promising. I argue that there are different perceptions of the future of the hydrogen technology field, which lie in certain ranges. These perceptions are based on specific assumptions about political, economic, social, and technological developments. From that, each expert derives the perceived dominant technology in 2035, which again manifests in beliefs about future technological consequences. Even if different base assumptions led to the same dominant technology for different experts, I argue that different experts selecting a similar combination of dominant technologies must be driven by a similar set of base assumptions about the underlying trends. The deriving ramifications for the technology field of hydrogen must thus be consistent for each unique set of assumptions.

On the one hand, experts' base beliefs are inherently difficult to measure or even articulate. On the other hand, experts' beliefs in technological dominance can be easily observed. Therefore, I propose to indirectly measure these underlying assumptions through ranking technologies within specific use-cases. I assume that experts would consequently rank technologies within a use-case similar if they share a similar set of underlying base assumptions. I, therefore, introduced Phase 1 of the Delphi study to use the ranking pattern of technologies by experts in the use-cases as differentiators for scenarios because (based on my assumption above) each set of underlying assumptions must then be inherently consistent (see Figure B-5).

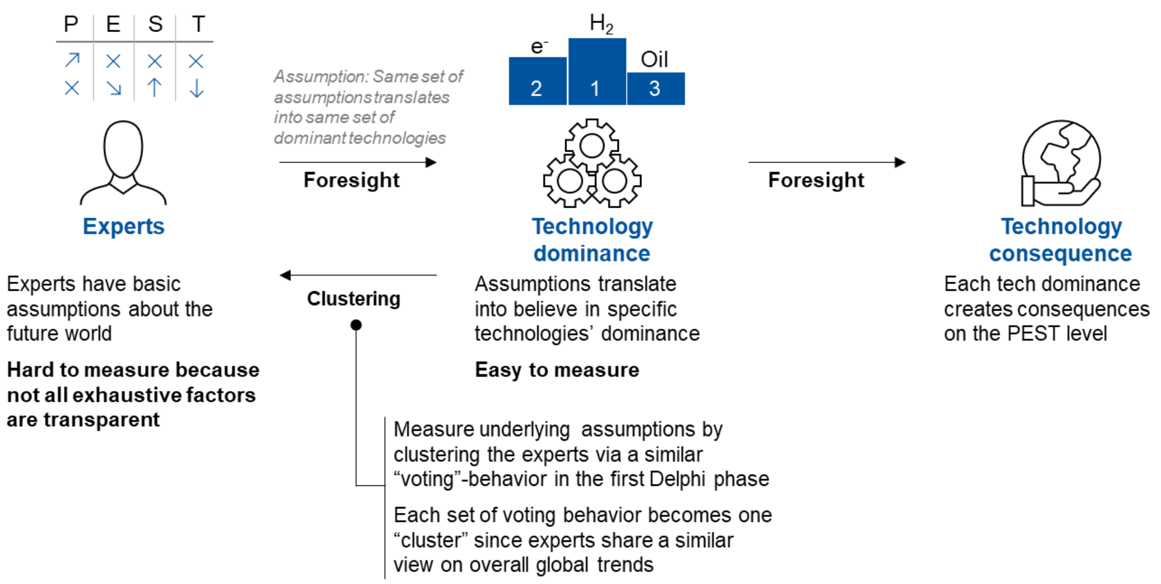

Figure B-5: Conceptual reasoning for scenario development approach

To follow this approach, I needed to identify similar decision patterns across the results of the 50 experts ranking up to 5 technologies (out of 10) for 19 different use-cases, I first decided to look only at the highest ranked (dominant) technology per expert. Second, I created an "expert-use-case-technology matrix". For this purpose, I coded each technology with a unique categorical identifier within each use-case. Then, I created a matrix containing this identifier for the highest-ranked technology per expert per use case across all use-cases. This matrix can be seen as a mathematical representation of each expert's individual voting behavior.

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

This approach identified two clusters of experts in each domain (hydrogen production, transportation, etc.) of the Phase 1. When an expert always fell into Cluster 1, I attributed the expert to Cluster 1 of the summary cluster. I did the same for Cluster 2. Those experts who did not answer any section in full or who fell for some sections in Cluster 1 and others in Cluster 2 were omitted from he scenario analysis. Ultimately, 20 were grouped in Cluster 1 (Scenario 1), 9 in Cluster 2 (Scenario 2), and 21 were omitted.

Scenarios for the future of hydrogen

When comparing the results in Table B-8, one can see that the highest divergence in the domain "supply", where the two groups ranked different technologies on top in 5 out of 6 topics, followed by "Heat/ Power/ Ind./ Feed" with 4 out of 6 and "Transportation" with 3 out of 7. This indicates a higher level of coherence and technological clarity in the transportation use-cases. Looking into the specific set of technologies, Cluster 1 shows a lower average TRL (technology readiness level) than technologies identified as dominant by members of Cluster 2. Additionally, Cluster 2 relies on hydrogen-based technologies in only three use-cases (excluding supply use-cases), whereas Cluster 1 sees hydrogen-based technologies dominant in nine use-cases. Experts from Cluster 1 also believe stronger in the self-reinforcing effect of technology rollouts than those from Cluster 2 and think that the biggest hindrance factors lay in economic and political reasons (compared to economic and technical for Cluster 2). Based on these findings, I call Scenario 1 "The Techno-Optimists-Scenario" and Scenario 2 "The Techno-Skeptics-Scenario".

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

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

Table B-8: Descriptive statistics for scenario comparison of Phase 1 (prognosis for the year 2035)

Scenario 1: The Techno-Optimists-Scenario

In the mind of the "Techno-Optimists," the hydrogen supply will be covered with green hydrogen produced with PEM electrolyzers, transported over long distances with hydrogen pipelines, stored in underground facilities, and distributed via existing gas networks repurposed for transport of pure hydrogen by 2035. The set of identified dominant technologies suggests that experts believe in a heavily defossilized world requiring high amounts of hydrogen.

Hydrogen pipelines require high investments and create a lock-in between provider and supplier, where especially the former only pays out when transported volumes are high (Borsboom-Hanson et al., 2022). Similar is valid for the exploitation of underground storage in, e.g., depleted oil and gas fields. Furthermore, the expert's belief in repurposing gas distribution networks suggests that they also believe that natural gas consumption will be reduced to a mere minimum, hence not requiring the distribution network anymore.

In transportation use-cases even the group of hydrogen-progressive "Techno-Optimists" do not believe in the dominance of fuel cells for any type of passenger car but see applications in other surveyed use-cases. In their scenario, both construction vehicles and heavy-duty trucks will run on hydrogen fuel cells, and bio-and synfuels will find applications in short and medium-haul aviation and large-scale container shipping. Similar conclusions can be seen in the domain of heat / power / industry / feedstock applications. There is no case for hydrogen-based technologies in heating of private and commercial buildings (dominated by heat pumps and teleheating), but experts believe in the dominance of H_2-based technologies in CHP (combined heat and power), high-grade industrial heat, long-term energy storage, and steel production.

The results of technological consequences (Phase 2, see Table B-9) draw a similar picture. When looking at the topics with the most significant divergence (>10%p difference) between the two expert clusters, ten projections stand out: In Scenario 1, experts believe it is more likely that more innovation in the hydrogen space is driven by startups (still below 50%). They also see consolidation in fuel cell- and electrolyzer companies less likely, suggesting they anticipate a greater need for these products. At the same time, the success of business models focusing on supply and demand balancing is rated much higher (15%p), indicating a more pronounced supply scarcity. In the domain of hydrogen supply, the formation of a "hydrogen" OPEC is more likely, which is coherent with the lower expectation of forming a consistent hydrogen trading market. Whereas in transportation, an insufficient use penalty becomes more likely (still on an unlikely level at 22%), and experts believe that a private buildup of refueling infrastructure for logistics companies might not be necessary. The most controversial topic among the two groups is whether the shift towards a hydrogen-based economy would lead to a major location shift of high-energy users. In Scenario 1, there is only a small likelihood of this happening. Housing experts believe stronger in new technology and digitization solving fossil-energy consumption rather than only efficiency gains (insulation, denser living, etc.).

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

(1: not probability but mode of 5-Likert from 1 = significantly increase to 5 = significantly decrease, 2: not probability but top-ranked answer, P / I / D = Probability / Impact / Desirability; P / I / D values are means)

Table B-9: Descriptive statistics for scenario comparison of Phase 2

This scenario renders the field of hydrogen technologies a crucial pillar to the overall defossilization of the world's economic system and sees the consequences of a shift towards a hydrogen ecosystem more positively. This aligns with a higher average technological openness of experts from Cluster 1. Analyzing the demographic differences of experts in the two clusters, I found that the experts in Cluster 1 were, on average, German (90%), Engineers (65%), and had a background in academia and research (45%). At the same time, the geographic region and the background were the biggest differentiators between the two groups of experts.

Scenario 2: The Techno-Skeptics-Scenario

The "Techno-Skeptics" foresee that the hydrogen supply will be covered with green hydrogen produced with alkaline electrolyzes (Wappler et al., 2022), transported over long distances with ships in the form of ammonia, stored in ammonia tanks, and distributed admixed in the existing gas networks by 2035. This set of technologies suggests that experts believe in hydrogen playing a role in defossilization, but to a lower extent than in Scenario 1, and relying on more proven technologies.

In transportation use-cases, techno-skeptics only believe in the dominance of fuel cells in heavy-duty trucks, while all other land-based transport is assumed to run on batteries. Additionally, experts believe in fossil dominance in aviation and shipping use-cases. Reliance on proven technologies can also be seen in the domain of heat / power / industry / feedstock applications. They argue that hydrogen-based technologies can only dominate in combined heat and power and steel production, while all other use-cases rely on technologies already used today. This aligns with the fact that experts saw much higher self-reinforcing effects for technologies in this domain, which promotes existing technologies. For technological consequences (see Table B-9), the comparison to Scenario 1 indicates that experts believe that innovation in the hydrogen space will come from incumbents, assume a stronger contraction of the number of fuel cell and electrolyzer producers, and believe in less importance of H_2 supply and demand balancing. Whereas in transportation, an insufficient use penalty is unlikely and a more substantial private involvement in refueling infrastructure for logistics companies is assumed. Furthermore, experts believe in strong relocations of hydrogen-dependent heavy industries in this scenario.

This scenario perceives hydrogen technologies as a puzzle piece towards full defossilization, but with only a minor role to play in selected hard-to-abate use-cases. These experts favor direct electricity use-cases. Looking into expert demographics, experts in Cluster 2 are German (67%), Engineers (67%), and have a background in business / industry (77%).

Discussion and Contribution

Implications for research and foresight methods

First my newly developed method attempts to provide a new approach for mid- and long-term forecasting of the development of broad technology fields. The methodology offers the possibility to create inherently consistent scenarios about future technology mixes solely based on Delphi survey data and thus makes a multi-method approach or mapping out an exhaustive list of underlying drivers redundant. This reduces the efforts of researchers and practitioners.

Staging two interconnected Delphi studies allowed me to analyze the interaction of cause (technology dominance and hindrance reason) and events (technology consequences). By this, I aim to ease an ex-ante planning and ex-post analysis of why my forecast might be correct or false. Implementing this approach in more Delphi studies would greatly increase future researchers' ease of validating the method's forecasting performance. I also argue that my scenarios are actionable for decision-makers since, over time, indications arise if a forecasted dominant technology mix would still be feasible. Hence, policy and decision-makers can "observe" certain events to decide which scenario track they are on.

Second, I complement existing Delphi studies on hydrogen (e.g., CIFS, 2021; Lee et al., 2022; Thoennes & Busse, 2014) by shifting the focus from individual hydrogen technologies examined in isolation to hydrogen as an integrated technology field. This technology field comprises distinct technologies that complement each other along the hydrogen value chain (production, storage, transport, and use) and compete with other non-hydrogen technologies for dominance in distinct application areas ranging from road traffic and aviation to heating and industrial applications. This approach is consistent with theoretical advances in technology strategy (e.g., Kapoor & Klueter, 2021), technology diffusion (e.g., Anderson & Tushman, 1990), and especially technology interactions (e.g., Sandén & Hillman, 2011) that highlight the interplay between distinct technologies—be they competitive, symbiotic, or parasitic—as a critical yet underexplored factor shaping technology diffusion. As I show, a field-level perspective that seeks to account for the multifaceted nature of technology interactions within and between technology fields can yield novel insights on the future diffusion of hydrogen that cannot be generated by conventional approaches focusing on individual technologies.

Implications for industry and policymaking

Promoting a specific technical solution is also a decision against promoting its alternative. The implications of my research can offer increased clarity on future developments. In general, for policy and decision makers and specifically for cross-sectorial state-orchestrated hydrogen clusters, I derive recommendations about where to focus investment efforts to develop the most needed hydrogen-based technologies for each application. I showed that the future of hydrogen can be powered by different technology mixes. However, bringing these technologies to market readiness in time to reach dominance in 2035 would require further development. From comparing the identified scenarios, I can thus conclude areas where to enhance and where to scale back public and private efforts.

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

In consumption use-cases, based on my results, the proliferation of hydrogen-based technologies for defossilizing land-based transport applications is unlikely, which opposes the view of the Hydrogen Council (2020, 2021) but is in line with the forecast of the IEA (2021) and the description of The Economist (2021). An exception is only the case of heavy-duty trucks. Even the group of hydrogen-progressive "Techno-Optimists" does not believe in the dominance of fuel cells for any type of private or commercial passenger cars. This finding disqualifies the technology from playing a major role in defossilizing transport. In 2020, 5.6 Gt of almost 8 Gt of CO_2 emissions stemmed from road transport (IEA, 2021a). Where passenger car transport produces 45.1% of all transport emissions (CO_2 Transport Emissions - Our World in Data, 2018). The challenge gets aggravated when considering that experts believe transportation use-cases are prone to be dominated by one single technology (battery electric vehicles in the case of passenger cars) due to higher path dependencies (benefits from mass production and required infrastructure). This will not even change if fuel cell electric heavy-duty trucks become dominant because experts expect a low level of inter-use-case benefits (low technological interdependency). Based on this, efforts from both private and public actors to bring fuel cell passenger vehicles to wide use should be limited to save resources for alternatives with greater economic and defossilization potential.

A similar conclusion is valid in (retrofit) private and commercial heating use-cases, where hydrogen-based technologies were not expected to become dominant. For these use-cases, experts believe in heat pumps and teleheating, both of which show higher technological readiness levels, have (partially) existing infrastructure, are expected to have lower running costs, and are already used today. This finding suggests that hydrogen networks supplying private and commercial housing for heating purposes are unnecessary, and funding and research efforts in this field can thus be reduced. This view opposes the forecast of the IEA (2021) but is supported by doubts about the cost-competitiveness of hydrogen technologies by the Hydrogen Council (2021) and Liebreich (2021).

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

The picture is different within industrial applications (combined heat and power, high-grade industrial heat, long-term energy storage, and steel production), where one (in some cases both) scenarios find the dominance of H_2-based technologies. This suggests that hydrogen should be promoted in these applications and that hydrogen networks (at least in 2035) can be limited to large-scale industrial consumers, reducing the necessary infrastructure build-up and thus speeding up decarbonization.

The cluster of techno-optimists had a significantly higher share of experts from Germany. In front of the backdrop of Germany's prominent national hydrogen strategy, generous incentivization schemes (Gül et al., 2019), the country's dependency on energy imports, and the associated media reporting, it seems natural to be more optimistic in Germany. However, one could argue that this positive feedback-enhancing environment could act as a "filter bubble", limiting technology openness and thus biasing decision-makers. Overall, one could summarize that in 2035 hydrogen will play a significant role in global defossilization but will do so primarily in replacing today's grey hydrogen and venturing into industrial and power applications. The significant uptake of other hydrogen-based use-cases potentially falls into a later time frame or misses the infliction point for proliferation.

Limitations and further research

Of course, limitations and associated research opportunities arise from two dimensions: the hydrogen technology field and the Delphi method. First, my newly developed Delphi-data grounded scenario approach needs testing and validation. Second, some of the findings reported in the study are either controversial or could not reach consensus while being perceived as highly relevant for the future of the hydrogen technology field. I am convinced further research on these questions is necessary.

To the best of my knowledge, no previous research ran a similar approach to forecasting technology fields, and I suggest implementing this methodological contribution to the Delphi method in other research settings to validate my approach further. I argue that other researchers could apply this technique in another setting where a multitude of competing and complementing technologies interplay and thus form a broad technology field. These could include "artificial intelligence", "human space exploration", "personalized medicine", "3D printing", and more.

Finding that experts' arguments for hydrogen were more often placed on a socio-economic level while con-arguments were situated on the use-case level poses a significant threat to the roll-out of hydrogen-based technologies. System-level advantages do not generate payouts directly to end-users. I expect actors responsible for introducing these technologies to usually decide based on benefits for their specific case, which would mean they do not optimize overall system performance. I am convinced that further analyzing this phenomenon, specifically for hydrogen-based technologies, is of interest from a policy perspective.

My study found that actual domain experts were always more skeptical regarding green technologies' dominance in their field than "adjacent" experts. I was further able to show that experts translated their expertise with a specific technology (based on their use-case) to the application of the same technology in other use-cases where, again, they were more skeptical. I suggest studying this effect of expert-skepticism and its influence on technology forecasting in other research settings.

On top of this, I found the projection "Location shift" to be highly debated among the experts and answered diametrically differently between the two scenarios. Since a potential emigration of energy-intensive industries poses an important threat to regions with solid manufacturing footprints and low energy resources (such as Germany). I state that a deeper understanding of the underlying drivers is necessary, potentially through applying my research approach in other similar geographical settings.

Lastly, I suggest studying the interaction of the two scenario expert groups. Since the experts for this study were sourced from the same channels, experts likely encounter each other daily. Thus, I ask: 1) How did two opposing views emerge among the experts, and 2) Which tensions arise from these daily interactions?

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Appendix

Appendix B-1: Overview short listing logic for use-cases

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

Appendix B-2: Coding table comment analysis
(quote-level only exemplary, multiple codes per comment allowed)

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

Appendix B-3: Interdependency matrix of projections and use-cases (abbreviated to show only projections and use-cases selected for Delphi study)

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

Essay 2: The Serendipitous Change Process of Incumbents' Org. Identity
A Longitudinal Comparative Case Study during Oil and Gas Companies Sustainable Transitions

Abstract: The oil and gas industry significantly contributes to greenhouse gas emissions, but why are the industry's decarbonization efforts not meeting set targets? This paper investigates the role of sustainability-induced organizational identity change through a longitudinal case study of five oil and gas companies. Drawing on the theory of serendipity, I document the serendipitous nature of identity change by showing the interplay of managerial agency, fortunate coincidence, and environmental factors. My findings highlight the likelihood of discontinuous identity trajectories under these conditions and elucidate how activities at industry, organizational, and individual levels influence change dynamics. Practical implications for management, policymakers, and shareholders offer guidance for navigating sustainable transitions effectively.

Keywords: Organizational Identity Change; Theory of Serendipity; Sustainability Transition; Longitudinal Multi-Case Study; Incumbent Behavior; Oil & Gas Industry

Introduction

Sustainable transitions – large-scale changes necessary to solve "grand societal challenges" (Loorbach et al., 2017) – can yield opportunities for companies but also threaten their economic positions (Köhler et al., 2019). Whether companies can profit from them depends on their actions. Which behavior is deemed legitimate (internally and externally) in this context largely depends on companies' organizational identities (OI) (Albert & Whetten, 1985; Ashforth & Mael, 1996; Hannan et al., 2007).

Deviating from OI's initial conceptualization, research sees it as evolving over time (Ravasi & Schultz, 2006; Tripsas, 2009), changing either continuously (Gioia et al., 2000; Hamilton & Gioia, 2016) or discontinuously (Biggart, 1977; Reger et al., 1994). During this, multiple partial identities can co-exist (Ashforth & Mael, 1996) and various mechanics are at play on different levels (individual, organizational, industry), inhibiting or promoting change (Dutton & Dukerich, 1991; Gioia et al., 2013; Schultz & Hernes, 2013). Consequently, OIs can be seen as guideposts for developing routines and capabilities (Kogut & Zander, 1996) thereby steering companies' responses to influences such as pressure to develop sustainable business models.

Thus, to support sustainable transitions, a company's OIs must evolve before business models are altered (A. Hamilton & Gioia, 2009; Schultz, 2022). This is especially relevant for incumbents since legacy identities shape their change process (Wood & Caldas, 2009). However, since companies' sustainable transitions can happen during industry decline, which severely impacts organizational identities, influencing factors are complex and intertwined (Kivimaa & Kern, 2016; Turnheim & Geels, 2012). Despite this, the context of organizational identity change during sustainable transition is rarely addressed explicitly. Chong (2009), Frostenson et al. (2022), and Glavas & Godwin (2013) solely focus on the individual level. Abraham-Dukuma (2021), Hartmann et al. (2021), and Shojaeddini et al. (2019), resort to only implicitly incorporate research concepts related to organizational identity. And the efforts of Kenner & Heede (2021), Mäkitie (2019), Sharma (2000), and Shojaeddini et al. (2019) do not address the interplay of drivers and fail to tackle multiply levels of influence. This is troublesome since sustainable transitions are complex multi-actor processes (Köhler et al., 2019). Furthermore, current research sees sustainability-induced identity change as positive, one-directional, and self-reinforcing (A. Hamilton & Gioia, 2009), which mismatches the observable company behavior (Agnew et al., 2024; Bousso, 2024). Only recently has the scope of research on organizational identity change in the context of sustainable transitions broadened, e.g., to incorporate managers' narratives, institutional pressure, the interplay of different identities and green beliefs' (Kiefhaber et al., 2020; Liu et al., 2022; Onkila et al., 2018; Ratnawati et al., 2024).

Nevertheless, neither of the studies draws on existing OI change processes to explain company behavior during sustainable transitions, nor did they formulate a new sustainability focus OI change model. Sustainable transitions and their mechanics differ from those of other transitions, e.g., technological innovation (Köhler et al., 2019; Si & Chen, 2020). For example, sustainable transition must not make companies unprofitable quickly (Bousso, 2023) and must not disrupt their value propositions since their products are still needed to satisfy human needs (Marchionna, 2018). This removes the immediate economic compulsion for change. Considering this, it remains unanswered how a process of sustainability-induced identity change might unfold (if at all) and how it overlaps, interacts with, or differs from existing identity change. The purpose of this paper is thus to answer the questions:

1) How and why do incumbents move from their traditional to a sustainable business? And,

2) how does the identity change process unfold in their sustainability-induced transitions?

An ideal setup to conduct this research is the global oil and gas (O&G) industry. O&G incumbents are among the biggest emitters (Kenner & Heede, 2021), and their defossilization efforts are falling short (Dietz et al., 2019; Green et al., 2021). However, a faster transition might benefit O&G companies (Hansen, 2022; IEA, 2020), as shown by a few examples of successful transitions (Abraham-Dukuma, 2021). Consequently, I ran a longitudinal comparative case study across five European O&G companies (Ørsted, ERG, ENI, Shell, and TotalEnergies). I conducted 23 interviews with employees and industry insiders (investors, consultants, and researchers). Additionally, I complemented this data with publicly available interviews, corporate reports, news articles, strategy documents, and industry publications.

The study contributes two-fold. First, prior research has highlighted the importance of managerial agency and institutional forces in shaping organizational identity change and reconstruction (Gioia & Thomas, 1996; Schultz & Hernes, 2013). I draw on Busch's (2022) conceptualization of serendipity to complement the literature on identity dynamics by documenting the often serendipitous nature of identity change processes. I show how the interplay of managerial agency, fortunate coincidences, and the present environment shape OI trajectories. I find discontinuous trajectories are more likely when 1) a priorly broadened identity changes the framing of sustainability-induced change from a threat to an opportunity, 2) while market conditions are suitable for trialed sustainable business models to scale, and 3) a sudden impetus discredits “traditional business model”-supporting identities. This is a meaningful extension to extant conceptualizations of identity change because it explains the interaction of contesting idiographic identities and under which circumstances added identities substitute historical parts; a case especially prevalent during incumbents sustainable transitions.

Second, prior research has examined organizational identity change either at the level of the industry (He & Baruch, 2009), the organization (Tripsas, 2009), or its members (Onkila et al., 2018). I show how activities at these three levels interact in shaping OI trajectories, especially in the context of sustainability-induced change. I can demonstrate how the transformation of peripheral companies' domain identities serves as a deterrent to isomorphic changes within the industry. This is a meaningful extension to extant conceptualizations of identity change because it explains change or stability in multi-actor processes. Lastly, I highlight practical implications for management, policymakers, and shareholders. I do this with a vivid illustration of oil and gas companies' sustainable transition, including an analysis of transition dynamics, such as key events, driving forces, and barriers along Geels' triple embeddedness framework (Geels, 2014).

Conceptual Background

Organizational identity

"Identity serves as a guidepost, directing the development of some routines and capabilities over others and reinforcing some beliefs or others.[...] procedures, information filters, capabilities, knowledge base and beliefs of an organization all reflect its identity." (Tripsas, 2009)

Organizational identity is at work on different levels of an organization – individual, division, organization, etc. – (Ashforth & Johnson, 2002) and plays a role in a company's ability to adapt to change (Tripsas, 2009; Tushman & Anderson, 1986). Organizational identities comprise broadly defined concepts, such as missions, visions, values, beliefs, company goals, and basic operating procedures (Albert & Whetten, 1985; Ashforth & Mael, 1996). This intertwines it with organizations' practices, skills, capabilities, and routines (Kogut & Zander, 1996; Nag et al., 2007). Members of the organization see organizational identity as the central, enduring, and distinguishable core of an organization (Albert & Whetten, 1985). Identity guides organizational action through interaction with corporate strategy and daily work (Ashforth & Mael, 1996; Kogut & Zander, 1996). As such, the answer to the question of "what a company is" necessarily implies guidance for "what a company should do" (Anthony & Tripsas, 2016; Bövers & Hoon, 2021).

From this, different perspectives on the emergence of organizational identities evolved (Gioia et al., 2013). The perspectives largely agree on the internal source for defining the organizational identity via internal procedures (social actor), sensemaking and -giving processes by organization members (social construction), and legitimization by institutional forces (institutional perspective) (Gioia et al., 2013; Ravasi & Schultz, 2006). Only the population ecologists view identities as derived from the outside (externally), classifying the companies into specific categories (Hannan et al., 2003).

Organizational identity dynamics

Much disputed and deviating from the initial conceptualization, the answer to "what a company is" can and sometimes must be changed over time (e.g., Nag et al., 2007). Consequently, researchers recognized organizational identity as unstable and dynamic, incrementally changing over time (Ravasi & Schultz, 2006; Tripsas, 2009). Different change trajectories exist. Identity can adapt continuously while retaining coherence, conceptualizing identity as a viscous flow (Gioia et al., 2000; A. L. Hamilton & Gioia, 2016). Juxtaposing, Biggart (1977) sees change as discontinuous, while Fiol (2002) highlights that discontinuities happen when incremental change is insufficient, requiring radical change (Reger et al., 1994). In particular, in times of "temporal identity incoherence", leaders benefit from exploiting the identity discontinuity instead of understanding identity as continuous (Hampel & Dalpiaz, 2023). The identity shift happens through "substitution" (replacement of identity) and "addition" (adding of an identity) (Albert & Whetten, 1985). Change can occur on different levels and be induced and obstructed in various ways.

On the individual level (micro-level), there is the desire for identity continuity, which effectively slows change (Erikson, 1968; Mead, 1934). Similarly, social identity (Brewer & Kramer, 1985) leads to identity preservation when parts of the identity are threatened. Failing to make sense of the change, members resort to interpreting information from the company's identity perspective, thereby enforcing it (Gioia et al., 2013). The macro-level (organizational/institutional) barrier is centered around the concept of "centrality", where the "core" of an organization is deliberately protected (Corley et al., 2006). It generates legitimacy from stakeholders (Hannan, 2005; Hsu & Hannan, 2005; Pólos et al., 2002; Tripsas, 2009), thereby creating "institutional pressure" to adapt to presumptions about the company's category (Benner, 2007; Porac et al., 1999; Tripsas, 2009). All this creates inertia (Hannan & Freeman, 1977). Even if companies announce a strategic change, attempt to change knowledge and routines, and start implementing structural changes, this inertia can lead to companies reverting to their original identity (Nag et al., 2007), obstructing the envisioned change.

On the other hand, research knows change-promoting impetuses rooted internally and externally in an organization (Gioia et al., 2013). For instance, legitimization pressure promotes change (Glynn & Abzug, 2002). He and Baruch (2009) showed how institutional changes led to identity issues and the evolution of a new identity in a UK-building society. Dutton and

Dukerich (1991) presented how discrepancies between external and self-perceptions trigger identity change at the New York Port Authority. Gioia & Thomas (1996) and Schultz & Hernes (2013) studied the influence of future self-perception on today's identity compared to remembered past identities in the context of US Universities and LEGO. All four examples required a nominal-actual comparison, which involved managerial agency. Lyle et al. (2022) showed that this leader-driven agency can successfully address threats to identity. However, challenges arise when leader-envisioned identities are perceived as "incoherent" with the current identity (Hampel et al., 2020; Jacobs et al., 2021), making purely top-down-driven change difficult even if originating from legitimization pressure. Involving active culture management (He & Baruch, 2009), steering impression and legitimacy perception (Dutton & Dukerich, 1991), and evoking memories and future claims of identities (Schultz & Hernes, 2013) are only a few of the potential success factors.

Another factor is technology, both a source for and a context of change (Anthony & Tripsas, 2016). Technologies and innovations can be seen as "identity-challenging", "identity-stretching", and "identity-enhancing" (Anthony & Tripsas, 2016), distinguishing and explaining how the innovation is perceived through the organizational identity (Tripsas, 2009). During change, multiple partial identities can emerge and co-exist in organizations (Ashforth & Mael, 1996). Particular business models and technological innovations can lead to this phenomenon. New sub-unit identities allow innovation, while identities of existing units enable companies to continue their traditional business, potentially creating tension between antagonizing "ideographic" identities (Albert & Whetten, 1985; Paul, 2023). Tripsas (2009) used a digital photography company's case to illustrate this identity ambiguity exists in technology-induced change and created a model of companies' identity change processes that incorporates it. She created a three-stage process describing 1) How the original identity is supported, 2) a time when the identity remains ambiguous, and 3) a new identity emerges. Moreover, she conceptualized external imperatives as causes for a subsequent identity realignment (Tripsas, 2009).

In this context, framing is a relevant success factor that influences identity change trajectories due to its psychological and behavioral nature. If identity is threatened (mismatch of external recognition and internal image), organizations highlight parts of the identity that are not threatened and trigger change in other parts of the organization (Dutton & Dukerich, 1991; Elsbach & Kramer, 1996). Piening et al. (2020) described how, on an individual level, employees see identity threats as challenges to their own identity and respond to them. Another strategy is to realign the external reception with the internal identity (Dutton & Dukerich, 1991;

Gioia et al., 2000; Gioia & Thomas, 1996), seen in companies' "greenwashing". On the other hand, companies can embrace the identity threat as an opportunity leading to active reinterpretation and redefinition of identities (Ravasi & Schultz, 2006). Hence, to increase the likelihood of organizational identity change to occur, multiple promoters from different contexts must come together and change must be framed positively.

Identity dynamics during sustainable transitions

Organizations' sustainable transitions can but must not happen during industry decline, which is a context significantly impacting organizational identities (Kivimaa & Kern, 2016; Turnheim & Geels, 2012). Although organizational identities have been extensively studied generally, there remains a lack of understanding regarding the process of sustainability-driven identity change in four dimensions.

First, the explicit role of organizational identities in the success of sustainable transitions is understudied, particularly at the company level. Only a few studies explicitly view organizational identity change in the context of sustainable transitions. Bouncken et al. (2022) conceptualized "Organizational Sustainability Identity". Research on it is primarily focused on individuals (Chong, 2009; Frostenson et al., 2022; Glavas & Godwin, 2013); for example, individual orientation paradoxes ("business vs. values", "insider vs. outsider", and "short-term vs. long-term") (Carollo & Guerci, 2018). Those studies researching company-level sustainable transitions only implicitly touch on schemes related to organizational identity, e.g., social license to operate and managerial interpretation of sustainability as a trend (Abraham-Dukuma, 2021; Hartmann et al., 2021; Nilsen, 2017; Sharma, 2000; Shojaeddini et al., 2019).

Second, the interplay of drivers and the levels of influence impacting incumbents' transitions are poorly understood. Company-level transition studies focus on isolated transition-influencing factors that somehow impact identities; a holistic picture is missing. For example, in the O&G industry, internal factors include manager bonus mechanisms (Kenner & Heede, 2021), misfitting governance structures (Shojaeddini et al., 2019) and outdated practices. Additionally, Hartmann et al. (2021) studied low management commitment and Sharma (2000) investigated the organizational scope of change. Most recently Hartmann et al. (2021) and Mäkitie (2019) explored pre-existing knowledge and complementary assets while Rosenbloom & Rinscheid (2020) and Seto et al. (2016) examined the role of carbon lock-ins. External factors encompass a liquidity lack in renewable capital markets (IEA, 2022), geopolitics (e.g., oil price changes) (Morgunova & Shaton, 2022), and legitimization pressures from governments, activist investors, and the public (Shojaeddini et al., 2019; Vieira et al., 2021).

Third, sustainability-induced identity change is primarily seen as positive, one-directional, and self-reinforcing. A. Hamilton and Gioia (2009) described how sustainable activities can produce a positive flywheel effect, continuously shifting the identity to embrace more sustainable practices, a purely one-directional conceptualization. This mismatches with the observable world where companies oscillate between sustainability and traditional business-enhancing behavior (Agnew et al., 2024; Bousso, 2024; Gabbatiss, 2022; D. Noor, 2024; *'Pure Climate Vandalism,'* 2023).

Fourth, technology- and sustainability-induced change can coincide (Backer, 2008) and research agrees that sustainability can be an aspect of organizational identity reconstruction (Carollo & Guerci, 2018; Frandsen, 2017; Glavas & Godwin, 2013; Kiefhaber et al., 2020; Niinimäki, 2010; Onkila et al., 2018; Ratnawati et al., 2024; Simões & Sebastiani, 2017; Wright et al., 2012). Recent research broadened the initial individual perspective of sustainability-induced identity change to encompass 1) managers' narratives in response to regulation and market pressures (Backer, 2008), 2) sustainability reporting (Onkila et al., 2018), 3) institutional pressure (Kiefhaber et al., 2020), 4) the interplay between traditional and sustainable identities (Backer, 2008), 5) sustainable exploration and exploitation (Liu et al., 2022) and 6) green beliefs' role in forming a sustainability identity. Organizational sustainability identity was even shown to create a competitive advantage (Ratnawati et al., 2024). All these studies resort to analyzing the influence of single factors, missing the integration of the entire perspective and, in particular, the change process itself. Surprisingly, no study draws on the previously described change process in other kinds of organizational identity change. Thus, it is unclear how a process of sustainability-induced identity change is unfolding (if at all) and how it overlaps, interacts, or differs from other identity change processes (e.g., technology-induced). I wonder if a deeper understanding of sustainability-induced identity change can explain why „sustainability-related“ change sometimes leads to transitions and sometimes does not.

Method and Context

Case studies provide a detailed account of a unique or interesting situation of one or multiple research subjects, offering context and a more complete understanding (Neale et al., 2006). Case study methods can explain both the process and outcome (Soy, 2015), provide nuanced insights (Yin, 2009), capture the holistic nature of organizational life (K. B. M. Noor, 2008), and are thus well-suited for examining organizational identity-related processes. They can be used to provide descriptions and test or generate theory (Eisenhardt, 1989). The method of (multi-)case studies is common in sustainability (Köhler et al., 2019) and organizational identity research (Anthony & Tripsas, 2016).

Industry context and case selection

Today, 80% of primary energy consumption stems from fossil sources, causing CO_2 emissions, of which 56% stem from oil and gas (IEA, 2020). The industry is highly consolidated and consists primarily of incumbent firms. The ten most emitting global oil and gas (O&G) companies caused 25% of global fossil fuels and cement emissions between 1965 and 2018 (Kenner & Heede, 2021). Despite O&G companies' current shortfall in decarbonization efforts, the IEA (2020) describes the O&G industry as vital and argues that their financial heft renders O&G companies as core investors in the future energy transition. However, looking at overall investments in sustainable technologies, O&G companies contribute marginally to the proliferation of these technologies. In onshore wind and solar photovoltaics (PV), their global investment share is below 1%; in offshore wind and biofuels, it is below 3%; only in carbon capture, utilization, and storage does it reach significance at 37% (IEA, 2020). This suggests that the industry currently misses out on these opportunities and might ultimately fail to enter them on a large scale, which puts it in jeopardy of becoming obsolete in the overall transition to renewable energy.

Special attention must be paid to understanding the magnitude of the challenge for O&G companies, which is unique compared to other industries and types of transitions: 1) O&G products are still needed to satisfy human needs (Marchionna, 2018). 2) They face solutions that are often less performant and more expensive. 3) The O&G industry continues to be profitable (Bousso, 2023), removing the immediate economic compulsion for change. 4) The industry's business model is inherently unsustainable (Hunt et al., 2022). 5) The pace of the O&G industry's transition is partially tethered to the speed of societal transition. Lastly, 6) the O&G industry’s internationalization complicates its transition; if selective O&G companies no longer produce oil, others will fill that void. All these factors differentiate sustainable transitions from disruptive – technology-based – innovations (Si & Chen, 2020). On top, and not specific to the O&G context, incumbents are reluctant to radical change (Geels, 2014), and historic sustainable transitions show they can sabotage change because of lobbying power, economic relevance, and financial lock-ins (Berggren et al., 2015; Fouquet, 2016; Morgunova & Shaton, 2022). Bringing them on a track to support and accelerate change is thus problematic (Fouquet & Pearson, 2012; Kenner & Heede, 2021; Wells & Nieuwenhuis, 2012). I consequently studied oil and gas companies' sustainable transitions from the early 2000s – marking the start of activities – until the end of 2022 in a longitudinal comparative case study (Siggelkow, 2007).

To study O&G companies' transitions, we need examples of transition leaders. I approached the case selection process from two sides. First, data-driven by compiling companies' decarbonization performance, and second, by talking to experts. I contacted industry observers for the latter and asked which players they perceived as leading. For the data-driven analysis, I was interested in environmental performance indicators. I found that, on average, 85% of O&G emissions stem from the usage of their sold products (Barbosa et al., 2021; *Corporate Data - CDP*, 2021; IEA, 2020). This led me to use normalized[2] Scope 3 emissions as a metric comparable to Vieira et al. (2021). Like Hartmann et al. (2021), I used the 2021 list of the S&P global top 250 energy companies to start my shortlisting. During my first interviews, I extended the list to include companies identified as leading in the transition. Like other researchers (Vieira et al., 2021), I collected the data[3] from the Refinitive Eikon®. Figure B-6 (left) shows the two O&G companies, reducing their emissions the most, were Ørsted from Denmark and ERG from Italy. Figure B-6 (right) shows ENI, TotalEnergies, and Shell as leading among the six supermajors. Based on this, I included these five companies in my sample, mirroring the findings of Cherepovitsyn and Rutenko (2022).

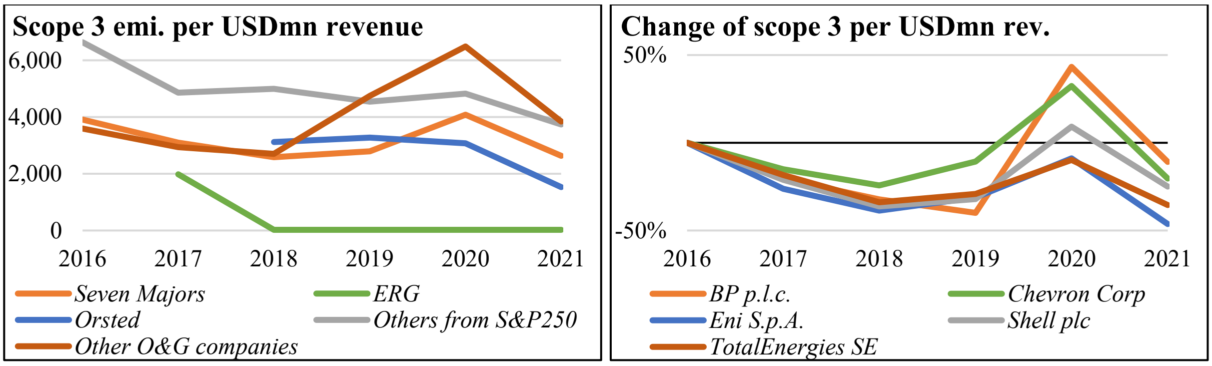

Figure B-6: Emission reduction data of sample companies
Left: Emission reductions per category (scope 3 emissions per million-dollar revenue)
Right[4]: Emission reductions for O&G majors (change of scope 3 emissions per USD mn revenue, 2016 base value); created by authors, based on Refinitive Eikon® data

Data collection and analysis

I followed the example of other sustainability transition studies case studies in the O&G industry and relied on multiple data sources (Garud et al., 2022; Halttunen et al., 2022; Ossenbrink et al., 2019). I desk-researched the companies' histories via company websites and newspaper articles (archival data). I complemented this with four publicly available interviews and conducted 23 semi-structured interviews (45-60 minutes) between January and September 2023. I sourced the experts via the researchers' network, online business networks, contacts at an industry congress, and pyramiding (von Hippel et al., 2009). Selection criteria were a multi-

2 I normalized with companies' revenues, which led to influences from oil and gas price fluctuations, distorting the comparison over time. However, these fluctuations affect all O&G companies equally ensuring comparability.
3 The reported data (especially on emissions) was only consistently available from 2016.
4 Normalization with revenue can lead to influences from oil and gas price fluctuations, distorting the comparison over time. However, these fluctuations affect all oil and gas (O&G) companies equally, which ensures inter-company comparability. The covid-pandemic-reduced oil prices in 2020 explain the peak in the data.

year experience at the respective firm or in the O&G industry, position in or access to the top management, and – preferably – a role in strategic decisions. I transcribed and coded all interviews. Lastly, I acquired 7 internal documents tackling the question of strategic company orientation and development of the O&G industry. In total, I relied on 63 documents and interviews for my analysis; Table B-10 shows the complete overview. I sourced the publicly available documents from company websites (especially investor relations webpages), academic libraries, O&G industry news websites, and Dow Jones Factiva®.

Source Type	ENI	ERG	O&G Gen.	Ørsted/ DONG	Shell	Total-Energies	SUM	Source Description
Internal Document		1	5		1		**7**	Internal corporate presentations, emission target library, portfolio review, strategy presentation on strategic response, internal paper on the perspective of industry convergence, hydrogen strategy paper
Own Interview	3	1	1	4	9	5	**23**	Interviewee roles: (Senior) partner in oil and gas consultancy, Head of renewable business unit, leading oil and gas researcher, former head of R&D, head of climate investment fund, head of PR, head of refining business unit, former head of exploration, independent consultant and former manager, chief strategy officer, professor for energy and resources, head of corporate strategy, head of stakeholder relations, global sustainability executive
Publicly available	4	7	1	8	8	5	**33**	Corporate history documents, books, scientific articles, published interviews, transcripts of corporate presentations, corporate sustainability websites and reports
SUM	**7**	**9**	**7**	**12**	**18**	**10**	**63**	

Table B-10: Data sources for analysis

Additionally, scientific papers touched on some of the sample companies' history or transition efforts selectively (Abraham-Dukuma, 2021; Backer, 2008; Capobianco & Basile, 2022; Gilardoni, 2020; Kenner & Heede, 2021; Larson, 2021; Li et al., 2022). Where applicable, I integrated the findings of these papers into my research. The coding was done with MAXQDA®. During the entire data collection, I only looked at past events and limited discussions with the experts about company announcements and plans to a minimum (Green et al., 2021). This mix of data sources and drawing insights from five case sources allowed me to triangulate and cross-compare my findings. I followed the approach of Garud et al. (2022) in first "creating a chronology of events". After this, I compared the cases and divided the process into transition phases. For each of these phases, I visually mapped out the factors (drivers and barriers) and key events (Langley, 1999), an important activity to understand the context in which organizational identities change and how they interact with companies' activities.

Deriving meaning from the gathered processual data requires an approach to discovering reoccurring patterns (Langley, 1999). Two researchers conducted the interviews to allow pattern recognition on different levels. They analyzed the collected data in depth, while the rest of the authors interpreted themes from an analytical distance. I first applied open and then axial coding to create first-order categories. I then deviated from the standard grounded theory approach (Locke, 2000) by grouping the first-order categories into existing second-order categories derived from Geels' (2014) "Triple Embeddedness Framework". The framework clusters these into environments. It is designed to study incumbents' behavior in light of grand societal challenges and brings together the system- and the organizational-level perspectives. It incorporates views from the major management study theories and is designed to be applied in case studies (e.g., Mühlemeier, 2019; Vieira et al., 2022). It aims to allow researchers to capture two-directional influences between companies and their environments. Specifically, it features organization identity as a component, enabling me to understand identity change in the context of the company's transition and influencing factors. Nevertheless, during the categorization, one group of codes did not fit: the category of internal actors, including management, employees, and shareholders. The deficiency was previously highlighted (Geels, 2014), giving me a reason to extend it to the quadruple embeddedness framework (Figure B-7). In the new layer, I looked at the interests, fears, desires, and dependencies of employees, management, and shareholders, who are the main actors in identity change. For my analysis, I created Figure B-8 and Appendix B-4 to B-6 to identify similarities and differences. Figures B-7 and B-8 also show the coding dimensions (environments, second- and first-order categories).

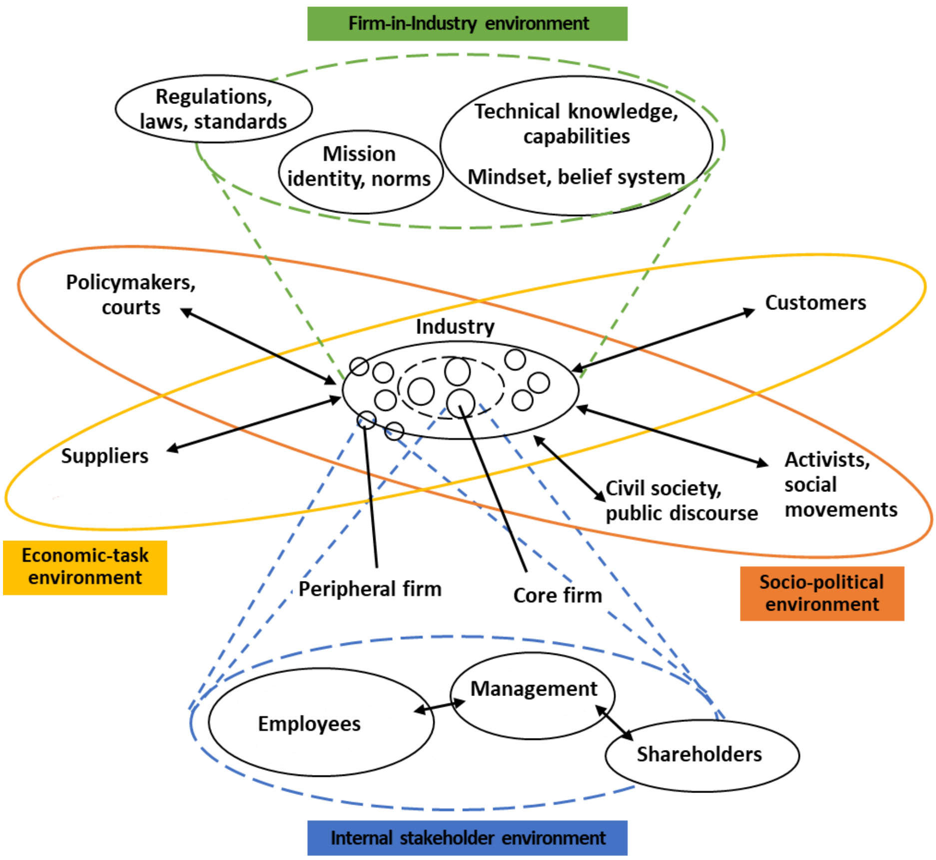

Figure B-7: Analytical (Quadruple Embeddedness) Framework based on Geels (2014)

History and Major Transition Events

To understand the identity dynamics during sustainable transitions, it is necessary to comprehend the sample companies' transition in detail. Therefore, I first provide an overview of the sample companies' history and events. I separate the section into four distinguishable phases. The phases are first described generally (Figure B-8). Second, I present the key events and milestones (visual overview in Appendix B-4) and how they delineate the phases. Lastly, I show the influence of transition-promoting and obstructing factors (visual overview in Appendix B-5 and B-6), particularly relevant for the deduction of identity dynamics.

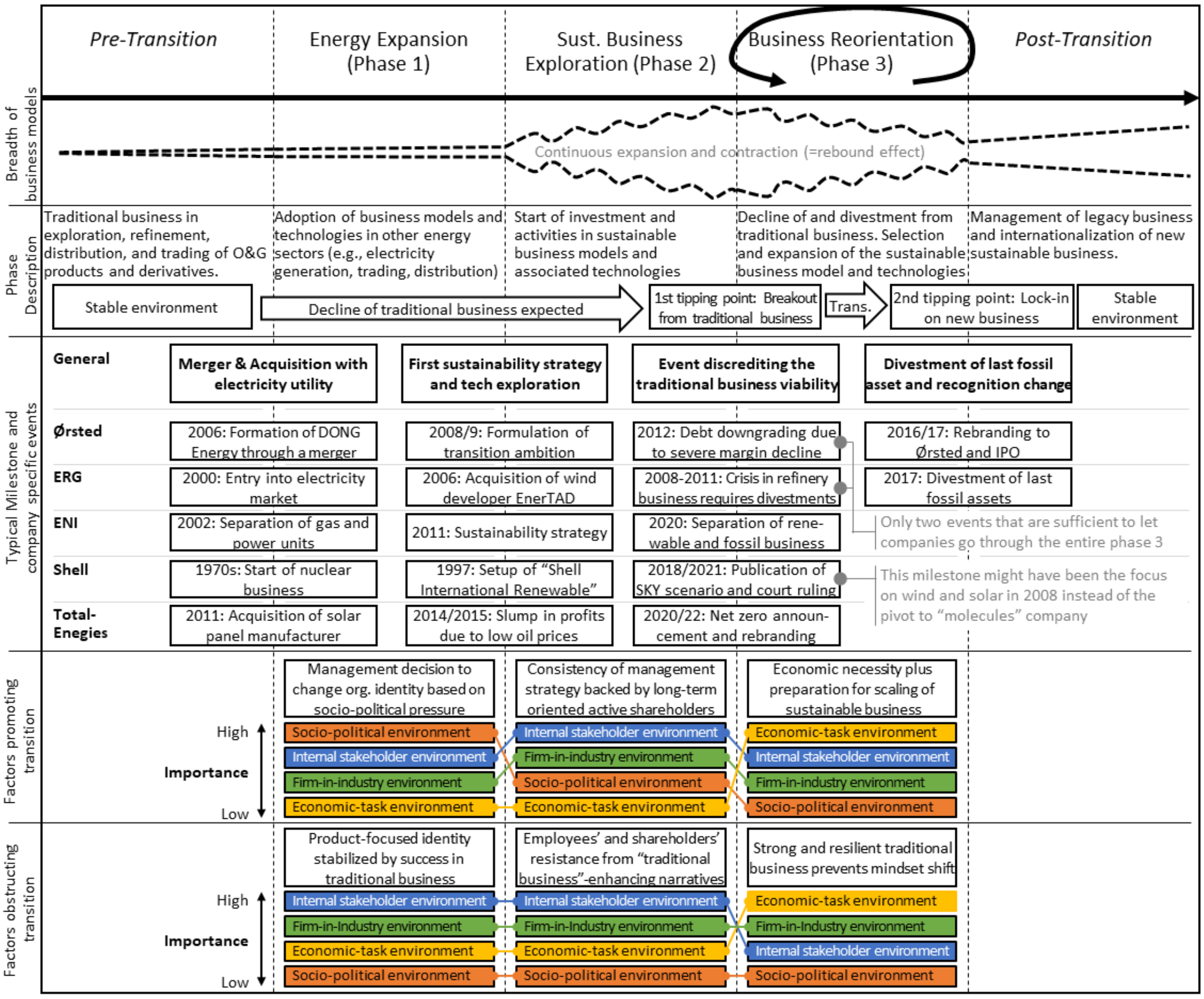

Figure B-8: Overview of O&G companies' transition process

Pre-Transition: Stable environments require little adaptation

The differences in pre-conditions between the cases are stark. The sample is divided into international oil companies (ENI, TotalEnergies, Shell) and smaller, more local O&G companies (ERG, Ørsted). Both ERG and Ørsted can be seen as peripheral firms in the oil and gas industry. They are small (>40x difference in revenues), locally focused (Denmark / North Sea and Italy), and have one strong majority shareholder (Danish state, founder family).

Before engaging in a sustainable transition, all sample companies saw a long period of stable environments. The traditional business of exploring, extracting, refining, trading, and distributing oil and gas products and derivatives had not changed in decades. Merely, the set of underlying technologies evolved gradually. The '70s oil crises had significant impacts on the competitive environment, and there were periods of market consolidations. Still, the influence on the overall O&G business model was perceived as low. My sample's integrated oil companies (IOCs, Shell, ENI, TotalEnergies) also expanded geographically (oil exploration locations and customer base). The most important structural change on the exploration side was the increasing importance of natural gas in companies' portfolios.

Phase 1: Entry into other energy markets broadens self-perception

The start of companies' transitions were marked by their first endeavors into other forms of energy – e.g., electricity or biofuels – thereby exploring new types of business models and technologies, often for the first time in decades. The expansion confronted the companies with handling a wider set of technological capabilities, increased organizational complexity, and consequently broadened their self-perception.

<u>Milestones and key events – becoming an energy company</u>

Ørsted began to acquire electricity companies in the 2000s and finally merged with several public utilities (power generation and distribution) in 2006. This merger changed the company's name from DONG (Danish Oil and Natural Gas, founded in the 1970s) to DONG Energy, rendering the company an "Energy Company". It now held assets in O&G as well as power generation, trading, and distribution. This was essential fir the company's quick departure from a pure fossil product focus. At a similar time, in 2000, ERG started its ISB Energy plant (combined cycle gas power plant), taking its first steps into another form of energy. The case of Shell is slightly different; it began its electricity ambitions much earlier, after the oil crisis of the 70s when entering coal and nuclear power. Nevertheless, this ambition was soon shut down. A scheme of reversing courses, which I will discuss later. No matter how and when, acquiring or building an electricity business was an innovation for each individual company.

<u>Identity change obstructing factors – traditional business' success creates locks-ins</u>

On the one hand, companies still had a strong product-focused corporate narrative, and at least in the case of the IOCs, the traditional business was still thriving. Interviewees told me that during this phase, employees said:

"*We are an oil company, we supply oil, and we make sure that the world keeps running*." (interview: SI_05, translated from German) and "*Ultimately, we are a technology company, always on the forefront of oil and gas technologies.*" (interview: SI_08)

Identity change promoting factors – first doubts about traditional business viability

On the other hand, the management made top-down decisions to diversify from a pure oil and gas business to other forms of energy. In the case of Ørsted and ERG, this was done to balance the first doubts about the long-term viability of the traditional businesses, which arose from decreasing competitiveness (decreasing margins and market shares) and slowly increasing pressure from the socio-political environment. The latter manifested itself in local demonstrations against fossil infrastructure projects, higher climate awareness in public and politics in the home jurisdiction, as well as the first regulations. The entry into the energy business broadened the self-perception of my sample companies, which started to see themselves as energy companies. This shift can be measured by the change in the definition of the target market share from the oil and gas market to the total energy market.

"A logic that appeals is that Shell [today] provides roughly 1% of global primary energy through O&G. And if you say, at the core, we are an energy company and want to retain market share, we still must have at least 1% of energy production in 2050."
(interview: SI_12)

Phase 2: Sustainable business exploration extents "valid" solution space

Companies' first steps towards adopting sustainable business models and technologies, as well as early fossil asset divestments, marked the beginning of this phase. My sample started via in-house exploration of underlying technologies or acquisitions of niche players. This resulted in an increasing breadth of business models and technologies, the adoption of which was not linear but underwent continuous expansion and contraction (conceptualized in Figure B-8). Despite this, the primary revenue and profit streams still came from the traditional business. Retrospectively, this period of explorative search prepared the company to initiate the transition when an opportunity to break with the traditional business arose. The end of the phase was, in all observed cases, a company's individual event majorly disrupting the business as usual, which led to the realization that the traditional O&G business would potentially not last.

Milestones and key events – First steps in sustainable businesses

In the case of Ørsted, two events were focal. First, the company faced severe local opposition to opening a coal-fired power plant near the German city of Lubmin in 2009. Second, climate change policymaking during the COP 2009 conference in Copenhagen (HQ location of Ørsted), increased the focus on climate protection in Denmark. This normative pressure led to the first formulation of a decarbonization ambition and visible behaviors.

First, all sample companies started partial divestments from fossil assets and selective decisions against pursuing projects related to the traditional business. Nevertheless, for the

IOCs in the sample, the declining importance of their oil business also meant doubling down on their activities in natural gas and actively promoting those as the "greener" alternative.

"I would say, at least in Canada, where there are a lot of high carbon intensity assets, Shell started to not actively chase projects around 2000. They chose not to pursue those A) because of economics and B) because of a shift in philosophy. So they divested many of their hefty oil sands assets by 2015." (interview: SI_13)

Second, companies engaged in explorative search for sustainable technologies and business models as alternatives. For example, ERG acquired EnerTAD, a wind developer, while Ørsted had been "lucky" in obtaining on- and offshore windfarms during their 2006 merger. It also started experimenting with retrofitting fossil power plants to be run on biomass, invested in wave energy and looked into battery technology. Next to operating wind farms, Ørsted moved up the value chain and acquired the wind farm installation company A2SEA. This marked the beginning of the project development business, which would become the core business later. Additionally, they partnered with the wind turbine producer SIEMENS, complementing the project development business. In comparison, the IOCs started their exploration much broader than Ørsted and ERG. The list of merger and acquisition deals during Phase 2 for these companies is long and marked by investments not only in renewable power generation (solar, wind, etc.) but also into technologies more adjacent to the traditional business like bio- and synfuels, hydrogen, carbon capture and storage and endeavors like electric vehicle charging infrastructure (e.g., NewMotion acquired by Shell), battery storage (e.g., SAFT acquired by TotalEnergies) and fusion energy (ENI cooperation with the MIT). Many of these early activities tended to be no success.

"The first commercial-scale wind farm that we built in Denmark was not a success. Actually, it did not work. The wind turbine did not perform the way we had hoped. We had to demount the wind turbines, bring them back to shore." (Ørsted, 2021)

In some cases, this "frustration" with the new business units led to rebound effects when activities in sustainable businesses were closed again or actively divested. In the case of Shell, this led to a learned connection between failure and sustainable businesses. As early as 1997, Shell started their "Shell International Renewables" business unit and became one of the world's largest solar manufacturers through a takeover of the joint venture with E.ON and Siemens in 2001/2002. The business was closed at the end of 2008 when Shell also halted its wind power activities. Later, the former CEO said, *"It was never a good business proposition. We could not make that work"* (Bennet & Mathis, 2023). What remained of the renewable business was integrated into the gas division. After a decade of activities, Shell almost entirely dismantled its renewable efforts. Jeroen van der Veer (CEO from 2000-2009) concluded that *"Shell is ultimately a molecules company"* (interview: SI_08) and should not focus on power but more on carbon capture and storage and biofuels. "*Fossil-fuel technological fascination is what this identity is about*" (Backer, 2008). Claiming to be a molecules company ultimately reduced the discrepancy between the company's primary business, the sale of O&G products, and its self-understanding. Mr. van der Veer's decision was again reversed under the following management of Peter Voser (2009-2014), who saw *"the real solid growth was in solar and wind"* (interview: SI_12), and Ben van Beurden (2014-2022), who doubled down on this. All back and forth strengthened the belief in the traditional business, preventing further and riskier endeavors into sustainable businesses. Compared to technological transitions in other industries, Shell and the other majors did not miss getting involved with them (Tripsas, 2009) but could not sustain their efforts. One interviewee suggested that Shell believed that, in the early 2000s, their traditional business would deteriorate faster. The fact that it did not happen actually stabilized it, rendering it "unbeatable".

<u>Identity change obstructing factors – Clinging to oil-focused narratives</u>

Three factors – in the internal stakeholder and the firm-in-industry environment – obstructed the sample companies' transition. First, interviewees mentioned that the traditional business was "too" successful and thus "too" resilient. Companies built this resilience against external shocks, partially by creating a natural hedge by covering the total value chain and diversifying geographically.

"If companies operate along the entire value chain, are present in various [geographical] locations, and are very big [system relevant], they become kind of immune to random effects shaking out the industry." (interview: SI_13)

Second, employees showed significant resistance to change, for instance, by fear of losing their high oil and gas wages. Third, in the case of IOCs, the heterogeneous shareholder structure with ever-changing majorities and clear margin expectations from pure financial investors obstructed management from long-term steering. Some investors perceived the O&G companies as "cash-printing" assets. Additionally, without a majority shareholder, management must fear a takeover when stock prices are low during transitions (interview: SI_08).

Furthermore, I found several narratives in the firms enforcing the belief in the traditional business on the one hand and discrediting the disbelief in the sustainable business on the other (overview in Appendix B-5 and B-6). A prominent one is the narrative that O&G can only transition at the pace of its customers, pushing the "problem" to the consumers of their products.

"For each sector, they are trying to sell decarbonized solutions to more or less the same customer base. However, I am not quite sure how fast the respective industries are changing. So you will have to go at the speed of respective industries. And as long as the customers still need diesel, they will sell it." (interview: SI_05, translated from German)

Identity change promoting factors – Consistency and shareholder support during exploration

In the case of ERG and Ørsted, I saw that (continuous) support from shareholders for the transition created the space for consistent manager action. It became apparent that this support is likelier when the companies have a majority shareholder (ERG: Garrone family, Ørsted: Danish state). These shareholders tended to be long-term-oriented and actively involved in the company's overall strategy. Management backed in such a way could run the company consistently through a period of external and internal volatility and even across management changes. Companies' anticipation of tightening market conditions for their fossil business further eased the managerial activity. For instance, companies feared losing their social license to operate or expect a tightening of regulatory frameworks, e.g., carbon taxes. The majority shareholders also provide take-over protection, but their transition-promoting stance is only given if they are not dependent on the O&G cash flows.

Another factor is the timing of companies engaged with specific technologies. ERG and Ørsted adopted their later proliferated, sustainable business early at the technologies S-curve and kept scaling them along the industry. My interviewees see this early adoption as paramount because it allowed the companies to trial and err during the period with high subsidies and slowly increased efficiency, thereby preparing them for the coming change.

"I really put emphasis on the fact that ERG and Ørsted were particularly good and visionary to anticipate a huge technology disruption, get the luxury to experiment with it and build capabilities in a highly subsidized period, and then scale it up rapidly." (interview: SI_15)

"Part of planning for the future was to say: we are developing certain technologies and business models to a point where we say if an event occurs that triggers a big push, then we are kind of done and in the starting blocks." (interview: SI_01 translated from German)

Hence, being a follower can make a company "miss the train" once technology starts scaling (interview: SI_09). The example of Ørsted and ERG suggests that companies must have their sustainable businesses and technologies "idling" to be prepared for virtuous dynamics.

Phase 3: The gradual amplification of the sustainable business model

A shock to the traditional business requiring companies to rethink their options marked the beginning of this phase. In comparison, the endpoint can be seen in the sale or closure of the last remaining traditional assets and a rebranding. This tipping point was reached when the sustainable business proved to be more profitable than the traditional. This emancipation from cross-financing acted as self-reinforcing and accelerated the change. Only two (ERG and Ørsted) of the five sample companies reached this point so far. They exited their traditional business and entered a new, stable environment with their sustainable business.

Transitioning from Phase 2 to 3 required a trigger event, an imaginable path to long-term profitability (possible solution to overcome the event's consequences), and limited options for the company to avoid the consequences with means from the traditional business. In other cases, companies resorted to strengthening their core business. This solution offered better plannable success in the short term and greater legitimacy in their self-understanding; it is what I saw at the other three sample companies.

Milestones and key events – A shock to the traditional business paved the way

For ERG and Ørsted, the initial shock to the traditional business arrived abruptly. Ørsted suffered from a severe margin decline in the gas business due to suddenly decreasing prices for natural gas in the US, which led to a debt downgrading by S&P Global Ratings. ERG had difficulties fulfilling its margin expectations during high volatility in crude oil prices. The company's absence from the exploration sector made the profitable operation of the refinery and distribution business harder. In the case of Ørsted, the external shock led to the necessity of severe actions. Based on the top-down decision of the company's then-newly appointed CEO (Henrik Poulsen, 2012-2020), Ørsted started to divest not only from fossil activities but also from renewable power generation (wave, wind onshore, and hydro) and electricity distribution. A portfolio assessment identified the development of offshore wind projects as the best compromise between leveraging existing competencies, generating competitive advantage, and matching long-term margin ambitions. Along the way, the company overhauled its operating model by laying off most personnel in its traditional business, easing a mindset shift about the company's future by replacing employees (Biggart, 1977; Gioia et al., 2013). Phase 3 required companies to unlearn past competencies and behaviors systematically and unravel existing organizational structures and procedures to excel in the sustainable business identified as most promising. The peak times of transition activity can also be seen in media reporting[5].

The shareholders, mainly the Danish state and later Goldman Sachs, supported the management. The divestment from the oil and gas business to Eneos and the rebranding to Ørsted coincided with becoming the biggest wind offshore developer globally and a subsequent IPO in 2016. This marks the phase's end. By then, Ørsted proved the sustainable business to be more profitable than the traditional one and increased shareholder value (2016 IPO to 12/2020 peak: 5.5x increase). Interviewees highlight that favorable market conditions supported the transition, such as low financing costs, public legitimization, and a severe uptake in global demand for renewable energy.

[5] I plotted the occurrence of articles between 2003 and 2022 tackling the topic of sustainability and sustainable transitions for each sample company and a control group. I based this analysis on FACTIVA data.

In Shell's case, on the one hand, a series of events (e.g., pandemic-induced low oil prices, results from internal scenario planning) destabilized the belief in traditional business, culminating in a court ruling to reduce Scope 3 emissions. On the other hand, multiple events marked setbacks: The backlash of Shell shareholders for reducing the annual dividend, leading to a refocus on the traditional business, and the reserve crisis of 2004 are just two. The latter had the potential to discredit the traditional business, but the opposite happened; Shell doubled down (interview: SI_08). The interviewees told me that several preconditions for the company (and other IOCs) to focus on a sustainable business have not yet been met.

First, in 2007, the global solar market (market size: 20.3 USD bn) was neither mature nor big enough to be a viable alternative for a supermajor like Shell (2007 revenue: 355.8 USD bn) (Shell, 2012; Statista, 2013). Second, the exogenous shock to the IOCs did not make the traditional business unprofitable. Opposite to the other two companies, the IOCs' traditional business was not vulnerable to supply chain disruptions because they were fully vertically integrated (natural hedge). Third, ERG and Ørsted did not see a perspective on maximizing the cashflows from their traditional business other than the sale of these assets. The IOCs concluded differently because they still generated stable profits, and their wealth in fossil assets was immense enough to deteriorate market prices in case of vast divestments. Fourth, their diversification of geographical and fossil energy sources (oil and gas) made them resilient to regulations and shocks. Fifth, the IOCs reached a systemically relevant size for energy security, making them subjects of national security.

Their resulting hesitant transition over time evoked two issues, hindering the transition. First, the market price for fossil assets shrank, leaving fewer proceeds from divestments to invest in building a sustainable business. Second, those sustainable business models that are now large enough for IOCs (e.g., solar and wind) have progressed in the technology lifecycle and now have higher entry barriers. The accordingly higher prices of sustainable assets also make acquisition strategies less attractive.

<u>Identity change obstructing factors – Narratives enhance traditional business resilience</u>

Starting with the internal stakeholder environment, employees' resistance to change remained a decisive factor in Phase 3. Compared to Phase 2, the increasing appearance of a cultural mismatch between people from the growing sustainable and the traditional business created tensions. Also, the heterogeneous shareholder structure continued to be problematic, especially when ESG-friendly (Environmental, Social und Governance) investors pulled out. That retreat of long-term focused, transition-promoting investors left those with opposing views in a relatively stronger position (interviews: SI_07, SI_19). For the level of firm-in-industries, there were three transition counterfactors: (1) problematic self-perception (too big to move, international companies can avoid national regulations, misconception about own transition speeds), (2) "traditional business"-enhancing and "sustainable business"-discrediting narratives (similar to Phase 2), and (3) problems in acquiring the required capabilities.

Some of these narratives are the following. First, "*energy security is more important than climate protection"*: The beginning of the Ukraine-Russia war in 2022 made energy security a critical topic, especially in Europe. The narrative that energy security can only be reached through oil and gas companies' traditional business gave companies "moral" leverage for their traditional business. Second, "*technology can save traditional businesses"*: Companies tend to believe that carbon capture and storage technologies can extend the lifetime of their traditional business. Third, "*investments into traditional business assets must be recuperated"*, which creates lock-ins. Fourth, "*companies with experience in greenwashing can use this capability to mask their actual transition efforts"*, thus releasing pressure. Fifth, "*the pace of the oil and gas industry's transition is tethered to the speed of societal transition"*. Sixth, "*if we no longer produce oil, someone else will*" (interview: SI_08).

<u>Identity change promoting factors – Towards a solution-oriented self-perception</u>

Significant transition-promoting effects were again situated in the realm of the internal stakeholder environment, namely the shareholder structure and the management consistency (compare with Phase 2). Additionally, Phase 3 was the first phase where companies started to embody a solution-oriented self-perception. The shift from "*We are an oil and gas company*" to "*We are an energy company*" unlocked the opportunity to embrace the sustainable business. This must be seen as a process supported by a strong company vision (a narrative about the future) and positive success experiences in a new business. This made companies more likely to trust the trend towards renewable energy, and that effects might occur that could accelerate the proliferation of their sustainable business.

"In 2008/9, we stood up and said that we were now building up capabilities for offshore wind, and it was not until 2012 that the economic push was there to change the business model. We already had a finished business model in our pocket, so to speak, which we only had to scale accordingly. Well, on the one hand, preparation is the be-all and end-all. You basically kind of force your luck a little bit." (interview: SI_01, translated from German)

Changes in organizational structures supported the increasing belief in the viability of sustainable businesses and the decreasing trust in traditional ones. In the case of Ørsted, the two entities for sustainable and traditional businesses – and with them, the organizations' self-understanding – were clearly separated (Hampel & Dalpiaz, 2023). During the transition, the company lost most of its employees who had previously worked in the traditional business.

Even though this is tragic for the individuals, it helped the company to tilt the balance toward those who embraced the (new) sustainable business model (Hampel & Dalpiaz, 2023). Additionally, companies' public announcements changed external recognition, which fed back on their self-perception, thus tilting the balance further in favor of sustainable businesses.

The socio-political environment also shaped the speed of the mindset shift by creating expectations about the future business environment, e.g., if companies believed that carbon taxes would increase and traditional businesses become less attractive, companies would adopt critical narratives faster (interview: SI_13). Similarly, a direct competitor that had already embarked on the transition created isomorphic pressure (DiMaggio & Powell, 1983) within the peer group of European IOCs (Shell, ENI, TotalEnergies). A mechanism with limitations (also see next section) and two-sided effects. Recently (2022, 2023), O&G companies scaled back on initially announced targets one after another (The Economist, 2023a). However, a controlled wind-down of the traditional business can create a positive flywheel. In the case of Ørsted, the shrinking of the traditional business reached a point where it was impossible to run it financially stable, requiring a further transition independent of other competitor behavior.

Post-transition: Full transition and roll-out of sustainable business

The positive momentum from Phase 3 reassured former O&G companies about the successful sustainable business model's internationalization and reapplication of the learned capabilities into adjacent sustainable business models and technologies. This followed a diversification strategy aiming to be less prone to disruption like previously encountered in traditional business. Ørsted, for instance, started the internationalization outside the traditional operating basin of the North Sea in 2017 through business in Taiwan and in 2018 with the acquisition of Lincoln Clean Energy and Deepwater Wind in the USA. Additionally, Ørsted began investing in the fields of onshore wind (reentrance), solar, energy storage, and hydrogen projects. This was accompanied by external recognition of their transition success by changing the sector from oil and gas to power.

Dynamics in Sustainable Transitions

In the previous section, I saw the centrality of concepts related to companies' organizational identity in responding to sustainability-induced change. In this chapter, I explicitly show its role by drawing on the existing understanding of identity change.

Sustainable transition-induced change is initialized by legitimization pressure

Before encountering the transition (see "Pre-Transition"), my sample companies solely faced identity-enhancing innovations (Anthony & Tripsas, 2016), during which they were not forced to radically change their organizational identity to incorporate new businesses. This history matters for flexibility in the following transition (Hampel & Dalpiaz, 2023).

Tripsas' (2009) model conceptualizes the emergence of a new – identity-challenging – technology that triggers the need to change the existing identity (the impetus for intentional identity shift). This does not align with my observation, where the external legitimization pressure (e.g., from the public and politics) on the traditional business forced the initial identity adaptation and thus enabled the trial of new technology and business models in Phase 1 (energy-related) and 2 (sustainability-related). This identity addition (Albert, 1995) led to two ideographic "co-existing" identities (Ashforth & Mael, 1996; Paul, 2023), which leaders tried to incorporate via broadening, aiming to include contesting stakeholders' views (Hampel & Dalpiaz, 2023). As a consequence, an ambiguous contesting but also symbiotic balance (Gersick, 1991) emerged between sustainable and traditional business-focused identities. The sustainable identity stream legitimized the fossil business, but in turn, its existence depended on the revenues of the other.

Broader identity definitions pave the way for identity pivots

The entry into the energy business (Phase 1) broadened the identity of my sample companies from "*We are an oil and gas company*" to "*We are an energy company*"; the shift can also be measured by the change in the definition of the target market share from the oil and gas market to the total energy market. This also entailed the beginning of a shift from product-centered identities to solution- or service-oriented identities, which eased the legitimization of sustainable business endeavors. This continuous change led to enhanced flexibility (Hannan et al., 2003; Hsu & Hannan, 2005). The orange path in Figure B-9 shows the broadening of the identity in Phases 1 and 2, given that the legitimization pressure is sufficient at the first equilibrium point.

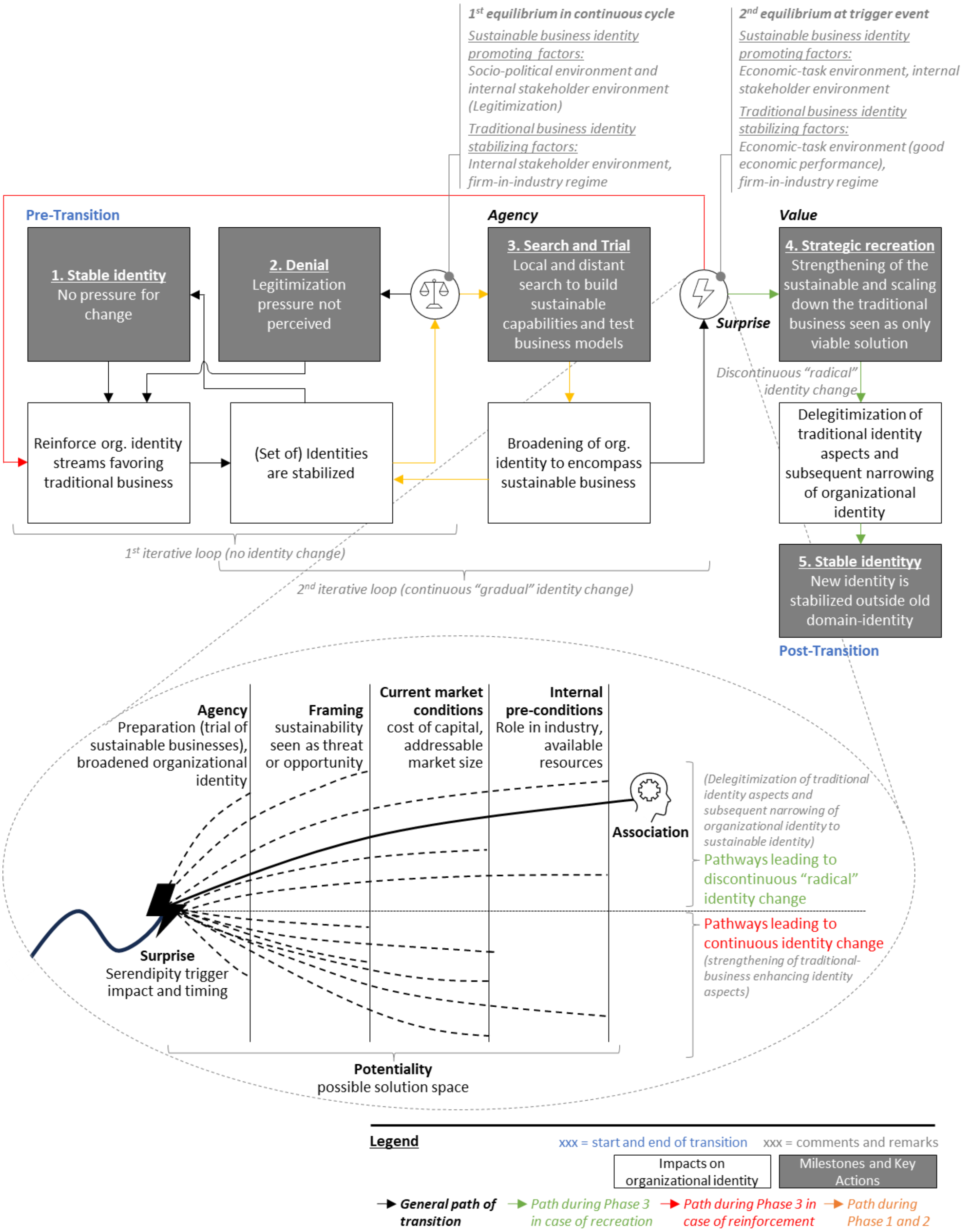

Figure B-9: Process for sustainability-induced identity change
Depiction inspired by Busch (2022) and Geels (2014)

The enhanced flexibility, in turn, enabled the organization to collectively see the rise of renewable energy technologies as potentially identity-enhancing (change of framing from threat to opportunity) but competence-destroying (Anthony & Tripsas, 2016) and were thus able to adopt it further (Tripsas, 2009). The identity literature knows this interplay between internal and external forces in the context of "memory cues" (Hampel & Dalpiaz, 2023). Legitimization issues alone were not enough to pivot to a new identity but prepared the organization to draw varying conclusions from shocks later during the transition. The wave-like evolution of legitimization pressure – e.g., during the Ukraine/Russia war, the need for energy security again legitimized the fossil business – and its weakening effect over time (Penna & Geels, 2012) are the reasons for its insufficiency to push the transition alone. Additionally, in the case of IOCs and opposite to ERG and Ørsted, the product-focused corporate identity is stabilized by the success and resilience of the traditional business.

A major external imperative is needed to trigger discontinuous change (Tripsas, 2009) through substitution (Albert, 1995). For this to happen, companies must strip those parts of their identity that still legitimize the traditional business. Substitution then happens either via extending the identity to "being a sustainable energy company" (ERG) or reducing it to a specific product or technology domain, e.g., "being an offshore wind company" (Ørsted) (Tripsas, 2009). My research showed that an "external impetus" substantially discrediting the viability of the traditional business triggered this alteration (ERG and Ørsted, see Phase 3 green path in Figure B-9). Even though some sample companies experienced threats to their traditional business model as well, their "external impetus" did not trigger the identity change but conversely strengthened the focus on their O&G business (Shell, ENI, and TotalEnergies, see Phase 3 red path in Figure B-9). Inertia can lead to companies reverting to their original identity even if the strategic change is announced, knowledge and routines are changed, and structural organizational changes are implemented (Nag et al., 2007). This can occur if companies fail to exploit an opportunity and suffer from falling profitability (Tripsas, 2009). Additionally, an increasing cultural mismatch between people from growing sustainable and shrinking traditional businesses, who have different internal identity perspectives, hindered change. Nevertheless, what circumstances then helped those companies proceed successfully?

Serendipity as the explanatory concept for identity renewal in sustainable transition

"Serendipity is a surprising discovery that results from unplanned moments in which decisions and actions lead to valuable outcomes." (Busch, 2022)

Tripsas (2009) sees the "external impetus" as the trigger for reconverging the external and internal perspectives. However, in sustainability-induced change, companies' internal perspective changes first, and external recognition follows. In the cases of Ørsted and ERG, I showed that transitioning from Phase 2 to 3 required a trigger event, an imaginable path to long-term profitability (possible solution to overcome the event's consequences), and limited options for the company to avoid the consequences within the traditional business. These attributes are the three distinguishing factors for serendipity occurring in the organizational context (Busch, 2022): From agency and surprise emerges value.

In my sample companies, the agency led to a broadening of identity (e.g., through sustainable business exploration) and a change in framing (sustainable business as opportunity), which widened the space for potential positive associations from surprising discoveries. The surprise came with external shocks to the viability of traditional business in its current state, questing business as usual and parts of the current identity. Trigger events "break expectations" and "change behaviors", such as values and norms (Ballinger & Rockmann, 2010; House et al., 2004; Morgeson et al., 2015; Pidduck et al., 2020). Great potentiality (Busch, 2022) resulted in a positive association; companies realized that the solution lies not in making the traditional business more efficient but in picking a new sustainable business from the "bouquet" of trialed businesses. Consequently, they underwent a radical discontinuous change. They adopted a new, narrower organizational identity, as seen in the case of Ørsted, which reduced its self-definition to "an offshore wind project developer". Value arrived in the form of increasing company valuations and returning to healthy profit margins (see ERG and Ørsted). The change is accompanied by a mismatch between internal and external company identities because the internal perception of the company's identity changes before the external recognition (e.g., for ERG recategorization by capital markets). This marks a difference from purely technology-driven change (Tripsas, 2009).

The influences on serendipitous associations

My findings also showed that the solution space for sustainability-enhancing associations depended on managerial agency, framing, companies' preconditions (e.g., the trial of sustainable businesses at the beginning of their technology's S-curve, resource constraints, shareholder structure), and the external market context (e.g., period of low capitalization costs). These act as filters for possible associations (see Figure B-9). In other words, with different external conditions, the association to solve the profitability problem by doubling down on the sustainable business would not have been valued positively. I also saw organizations generate value from serendipitous processes reversing their transition. An example of the traditional business strengthening after significant financial distress can be seen in PEMEX (not in panel), which doubled down on extracting fossils (The Economist, 2023b).

However, a similar agency and trigger event can also create value from a different association. The start of the Russia/Ukraine conflict and the entailing energy security debate marked a trigger event for forces stabilizing the broader energy company identity, creating value from a refocus on the traditional business (compare ENI, Shell, and TotalEnergies). Indeed, identity change is more readily accepted when the organization is destabilized (Gioia & Thomas, 1996) or faces existential threats (Biggart, 1977). However, the previously shown agency, market conditions, and the type of surprise define the solution scope in problematic situations and, ultimately the change direction (more traditional or more sustainable). I thus argue that organizations that face trigger events can either ultimately pivot to the sustainable business or experience another rebound "cycle" in which the traditional business-oriented part of the identity becomes strengthened compared to the sustainability-focused. I can see a series of such identity inconsistencies (Bövers & Hoon, 2021), where Shell changed its strategy, but the identity remained stable to a great extent (see "Phase 3: Events").

In theory, canceling the entire transition is also possible. However, in my sample, I do not find supporting evidence. Even though I am not the first to call for integrating the concept of serendipity in analyzing and crafting business strategies (Winter, 2012), I see this factor as a crucial element in incumbents' (sustainable) transitions, especially in their organizational identity change. I argue that this serendipitous process allows companies to alter their identity change trajectory from continuous to discontinuous (radical change). For this, it is necessary to view the incumbents in sustainable transitions as organismic (Cunha & Berti, 2023). They face deep uncertainty; Cunha and Berti (2023) thus call to understand the companies as "a flexible, adaptive system" in which serendipity is cultivated and seen as a dynamic capability.

Change of domain identity prevents isomorphism-induced transition of the industry

"The organization's identity legitimacy is determined by its conformity to the institutional norms, values, and regulations." (He & Baruch, 2009)

Because industry environments and socio-economic contexts influence organizational identities, research must consider institutional events (He & Baruch, 2009). In theory, the successful sustainable transition of organizations should entail isomorphism in the form of mimetic and coercive pressure (DiMaggio & Powell, 1983; Zucker, 1987). On the contrary, I found no evidence that the journey of the two sample companies functioned as a role model. Moreover, they are now perceived differently within the industry. As one interviewee put it:

"Oil and gas companies no longer consider Ørsted as an oil and gas company."
(interview: SI_05, translated from German)

Both – departing and remaining companies – benefit from this shift in domain identity (Kammerlander et al., 2018), which implies that there is a reduced or no influence on industry norms, standards, and practices. Aggravating is that the preconditions of Ørsted and ERG are perceived as non-comparable. The IOCs see themselves as the industry's core and shapers; Ørsted and ERG were identified as local players at the industry's edge. Therefore, I theorize that peripheral companies (Kammerlander et al., 2018) can depart from the established industry regime through the process previously described. Geels (2014) describes that "deviations from the prevailing industry norms are easier for peripheral actors”. Once such a company has exited the industry, its isomorphic influence on the remaining companies fades. Worst, the industry’s core members can argue that the peripheral departure process does not apply to them, strengthening the identity parts focused on the traditional business. The explanation leaves the possibility that a sustainable transition of one of the industry's core firms has a bigger impact on the remaining peers. When reverting to Figure B-9, one might characterize this process as a departure of companies from their original "home industry regime".

Discussion

Theoretical implications

With my research, I advance the discussion around the “intersection of organizational identity, collective identity, and the competitive landscape” (Anthony & Tripsas, 2016), as well as the understanding of sustainable transitions from an industry perspective (Geels, 2014). I show in the previous section in great detail that it is insufficient to explain organizational identity change in sustainability transitions solely with existing change processes. As presented in the previous section, I make two significant contributions. First, I complement the literature on identity dynamics by documenting the often serendipitous nature of identity change during sustainable transition. I show the dependence of change mechanisms on the interplay of internal agency, fortunate coincidences, and external forces, thereby creating a new process for sustainability-induced identity change. Second, I show how activities at three levels (firm members, organizations, and industry) interact to shape organizational identity trajectories.

Associated with these two contributions, I advocate understanding sustainability itself as an impetus of change rather than speaking of “organizational sustainability identity”, which would allow researchers to comprehend its interplay with other identity change mechanisms, i.e., technology-induced change. Associated with this, I find sustainability-induced change to be unique in the sense that: 1) Legitimizing the sustainability-enhancing parts of the identity is slow and steady while discarding the traditional one is abrupt and radical. 2) It is highly timing and market condition-dependent. 3) It is bi-directional (reversal is possible), and 4) it can alter organizations' domain identities, preventing coercive pressure from occurring.

Implications for practitioners

Understanding transition journeys can guide in managing them (Hartmann et al., 2021). I thus draw conclusions for the management, the policymaker, and the shareholder perspective. Historical impediments, including management changes and shifting agendas, have led to contradictions in organizational identities, which, in turn, have hindered transitions. Instead, management can show agency in preparing organizations for identity change by trialing sustainable business models, thus broadening the organization's identity. A practical approach is to actively widen the organizational identity by switching it from a product- to a problem-focused narrative. Managers can also change pre-conditions favorably, adjusting the serendipity solution space. For example, the strategic decision to exit relevant value chain segments, such as the closure of the oil exploration department, deprives future management of possible associations. In case of a shock, focusing on the traditional business might then be no option.

Once in the transition, maintaining a lean set of capabilities and sustainable business models is beneficial. Shifting the beliefs, mindsets, and values of the management, employees, and shareholders requires continuous, coherent steering and communication with all stakeholders on all available channels. In certain cases, the strategic separation of the traditional and sustainable business into distinct entities offers opportunities: 1) Wage variations and margin expectations can be accommodated in separate entities. 2) The divisions' focused business model enhances equity funding on the stock market. 3) Isolated steering mechanisms enable better management. 4) Dedicated employer brandings improve prospects for talent attraction. 5) The split allows the pursuit of different strategies.

Additionally, the role of technology strategies is paramount. Technologies should not be regarded as a reason but a platform for change. This approach necessitates a broad exploratory mindset, trialing different business models and associated technologies at the beginning of their S-curves. Entering these in later stages decreases attractiveness because margins decrease and (sustainable) target assets become costlier. While a broad technology approach is essential, investments should be placed carefully. Shell's decision to forgo wind and solar in favor of carbon capture and storage (CCS) and biofuels in 2008 illustrates this well. In the context of oil and gas, companies favoring "bridge technologies" (adjacent to traditional businesses) can pose challenges and create lock-ins. For example, CCS can be seen as a savior of the long-term viability of the oil and gas business, even though its current development pace may not be sufficient to enable this (interview: SI_18). Additionally, it often requires oil and gas infrastructure for large-scale CO_2 sequestration, which locks companies in on these assets. Incumbents naturally gravitate towards adjacent technologies to leverage their existing capabilities (interview: SI_13). I urge management to resist this temptation.

The transition of incumbents – especially in the oil and gas industry – entails a risk-profile transformation. Paired with an increasing focus on ESG (environmental, social, and governance) compliance, selective shareholders divest. Those who divest on these grounds surrender their influence to less ESG-focused investors. This can be a self-reinforcing path, where weaker ESG practices may lead more ESG-friendly investors to divest, perpetuating the shift. Institutional investors need to perceive the transition as a phase of vulnerability, marked by heightened uncertainty and risk. Thus, a majority shareholder (e.g., institutional investor, state entity) could protect against takeovers to enable the transition, which goes hand in hand with policies' role in guiding transitions.

Based on the serendipitous change process, policymakers could design incentives that encourage companies to engage actively with emerging technologies and sustainable business models. Subsequently, they could strategically introduce radical external shocks that disrupt established expectations regarding the future viability of the traditional business. These shocks may take the form of imposing substantial carbon prices or enforcing bans on specific products. The aim is to prompt an economic imperative for change. Consistency in these measures is paramount; policymakers must maintain a lasting commitment to policies reinforcing the perception that the traditional business' appeal declines. It precludes hopes of regulatory shifts that might again favor the traditional business.

Limitations and future research

While this study offers valuable insights, several limitations should be acknowledged. The study focuses on European oil and gas companies and their transition processes. As a result, the findings may not fully capture the dynamics and factors at play in other geographic regions or industries. Additionally, my sample misses companies that may have attempted but canceled a transition process. Thus, fellow researchers could increase the sample size to incorporate more international companies and "transition failures." Moreover, the dynamics should be researched in fields other than O&G to ensure that they are not industry-specific. Since the transition of O&G companies is heavily technology-related, I primarily compared sustainability-induced and technology-induced change mechanisms. When tackling industries other than O&G, academics could endeavor to research the interaction of sustainability-induced change mechanisms with other non-technological mechanisms. The ideal setting would be one in which the underlying business model is not inherently unsustainable.

While interviews with industry experts and stakeholders provided valuable qualitative data, it is essential to acknowledge the inherent subjectivity and potential bias associated with such data collection methods. Thus, my contributions to theory need to be strengthened by quantitative testing to provide further evidence.

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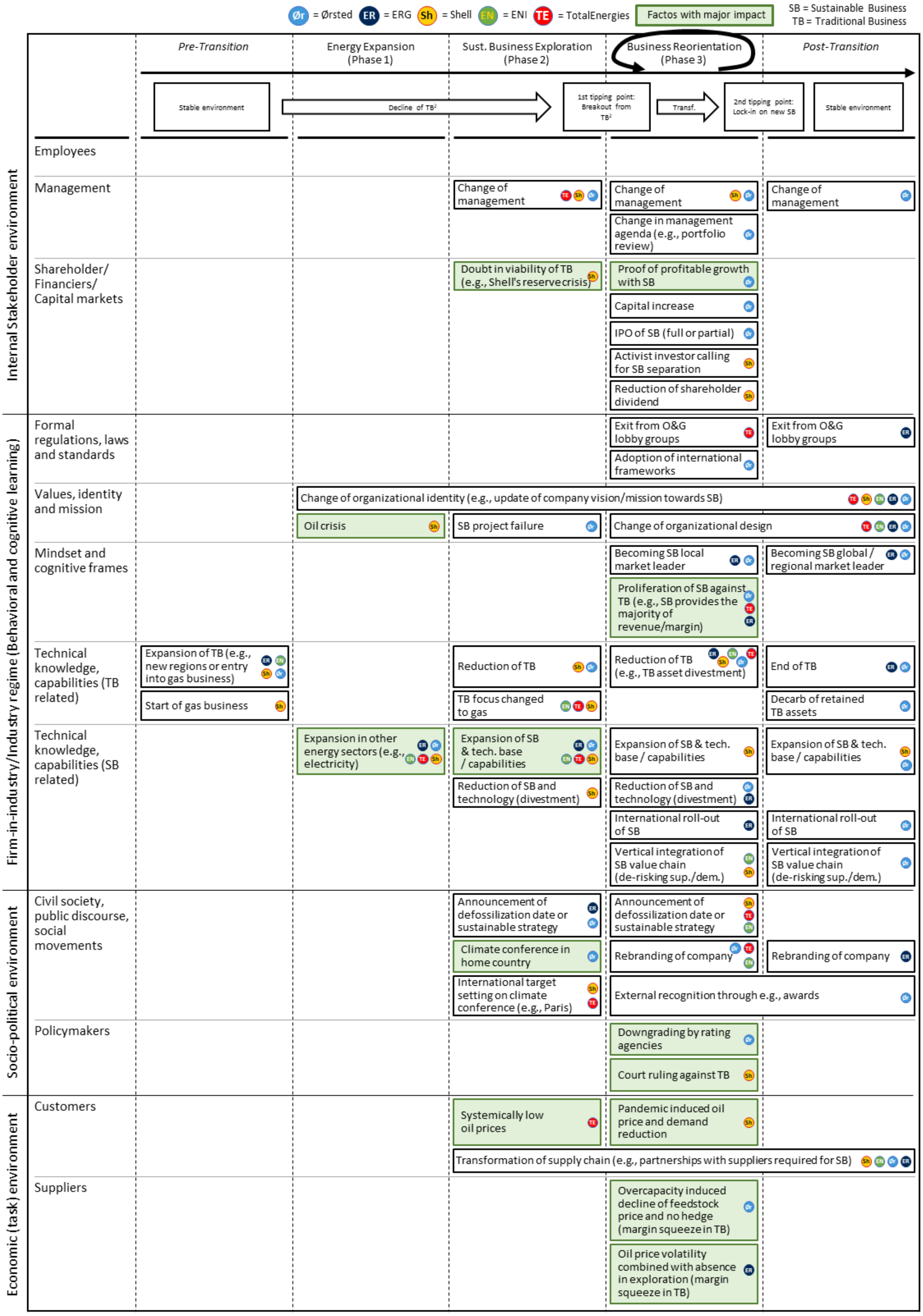
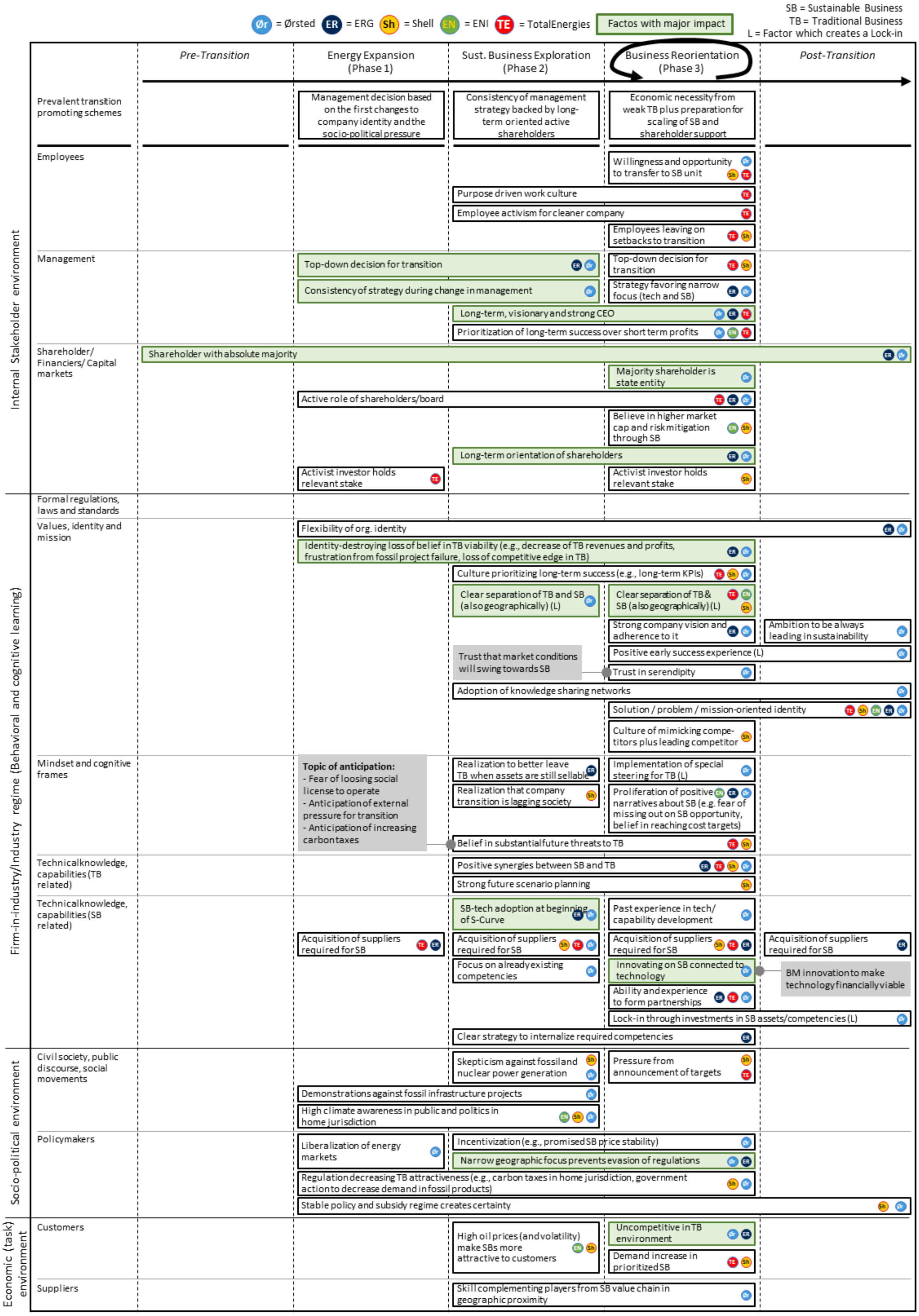
Appendix

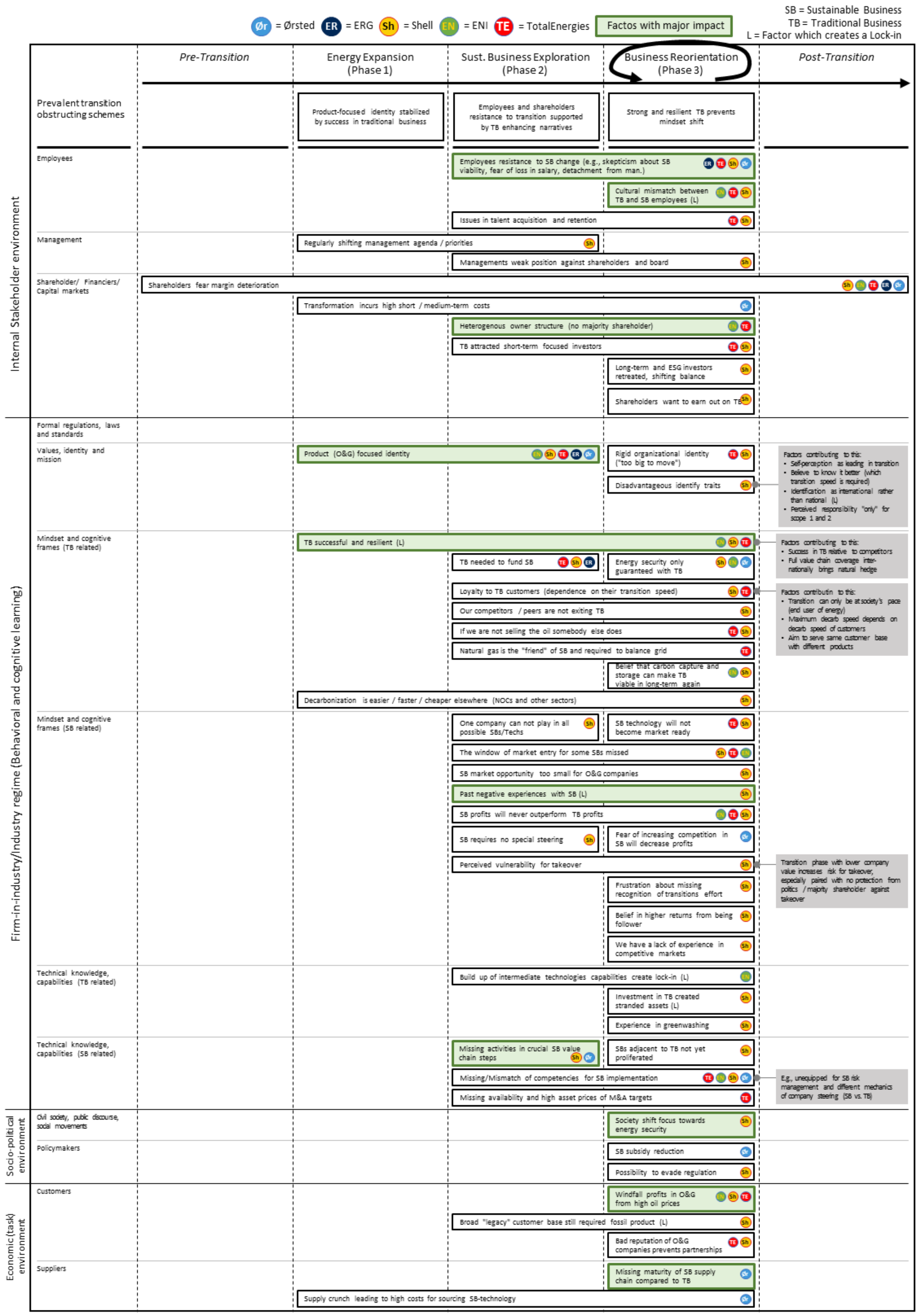
Appendix B-4: Typical key events and milestones in O&G transitions over time



Appendix B-5: Overview of promoting factors in O&G transitions



Appendix B-6: Overview of obstructing factors in O&G transitions



Essay 3: Mastering Emerging Technology Entries

How Timing in Uncertainty Treatments Influences the Performance of Incumbents' Technology Entries

Abstract: Emerging technologies drive economic growth and are characterized by novelty, fast growth, coherence, impact, and uncertainty. Companies facing these uncertainties employ varying adaptation strategies (e.g., diversification, discovery & search, experimentation & experience). During diversification into emerging technologies, timing is crucial for success, yet the literature often overlooks the portfolio perspective of incumbents. I address this gap by analyzing 386 venture capital (VC) funds, which is ideal due to their focus on emerging technology and good data availability. By combining the uncertainty reduction and entry timing perspectives, I show that early entry strategies yield superior financial returns, extensive information gathering often fails, and sectorial consistency is key in uncertainty reduction. I identify three interaction mechanisms of uncertainty treatments: supportive, complementary, and competing.

Keywords: Entry Timing; Uncertainty Treatment; Emerging Technology; Portfolio Perspective

Introduction

Emerging technologies are drivers for economic growth (Dosi, 1982). Novelty, fast growth, coherence, impact, and uncertainty define them (Rotolo et al., 2015). When faced with uncertainty, companies strive to obtain information or increase adaptability to ambiguity through (1) diversification, (2) discovery and search, (3) experimentation and experience, (4) flexibility and robustness, (5) social construction, and (6) scenarios and simulations (Arend, 2024a). Failing to employ these strategies bears risks (Kapoor & Klueter, 2020).

Hence, companies are permanently seeking opportunities from new market entries (King, 2008) while facing a growing number of emerging technologies (Kurzweil, 2014). These technology entries are prime examples of diversification. A multitude of factors (who, where, what, how, when) influence these entries (Zachary et al., 2015), of which the entry timing is the most prominent (M. B. Lieberman & Montgomery, 1988). The primary focus of the entry literature lies on (1) entries of individual companies in specific industries (Hawk & Pacheco-De-Almeida, 2013) and (2) cohorts of companies in isolated industries (Agarwal & Bayus, 2004). This neglects the perspective of incumbents for whom it is relevant to answer the question of how successful the portfolio of their technology entries (in one or more industries) really is. Strategically expanding this portfolio of technologies in industries is paramount for companies' growth and longevity (Markman et al., 2019) but fraught with uncertainties (Kapoor & Klueter, 2021). Currently, the literature cannot reliably answer which entry timing strategy yields the best results across a portfolio of emerging technology entries.

Consequently, companies spend resources on acquiring information, for example, in discovery and search strategies to reduce uncertainties (Zachary et al., 2015). However, this approach fails when information is scarce and short-lived (Arend, 2024b). In these situations, no reliable strategy can be created, or the strategy is already outdated at the time of employment (Marttila, 1999). Therefore, the extent of strategic planning should correspond to the level of uncertainty involved (Packard & Clark, 2020).

Theory suggests that companies can substitute missing information from search processes if they have past experiences in the market (Guillen, 2002; Simon & Lieberman, 2010). However, those insights focus on "direct" experience explaining success in re-entries. By definition, emerging technologies are new, precluding re-entries, which amplifies the importance of experience in other dimensions of entries where uncertainties exist – such as business models, applications, ecosystems, and user behavior (Kapoor & Klueter, 2021). Companies can thus mitigate entry uncertainties by entering technologies in familiar geographic or sectorial markets (Hilmersson & Jansson, 2012; Lamperti et al., 2020; M. B. Lieberman &

Asaba, 2006). Hence, consistency in sectors and geographies when entering emerging technologies (diversifying) would help to reduce non-technology uncertainties. This suggests two research questions.

(1) Which timing strategy is beneficial for incumbents entering emerging technologies?

(2) How do different uncertainty treatments – particularly strategic planning rigidity and consistency – interact with diversification in the context of emerging technology entries?

I analyze these questions with a unique dataset of 386 venture capital (VC) funds. The VC industry is ideal for my study since 1) VCs operating model is the identification of promising new markets (Gompers & Lerner, 2004). 2) The industry is transparent, with multiple databases available (Retterath & Braun, 2020). 3) Similar to incumbents, VCs influence the companies they invest in (Gao, 2011); 4) VCs show similar dynamics to corporate venture capital (CVC), which aims at taking minority stakes in startups to gain access to new technologies and their associated markets (Chesbrough, 2002; Dushnitsky, 2008). This data set allows me to study the performance of uncertainty treatment strategies – primarily diversification – measured as a fund's internal rate of return (IRR). This is a benefit over many entry timing studies, which look at survival rates or market shares (Agarwal & Bayus, 2004), measures with limited meaningfulness to success.

I study emerging technology entries from an incumbent's portfolio perspective, combining the perspectives of uncertainty reduction and entry timing. By this, I make three contributions. First, I elevate first- and early-mover advantages to the portfolio level, which is relevant for incumbents facing frequent entry decisions. My findings show that creator entry strategies yield superior financial returns, confirming first-mover advantages beyond survival rate-based measurements. These advantages are market-independent, suggesting that the discussion about market individualities is overstated. Second, I show that extensive information gathering can fail as an uncertainty treatment when dealing with emerging technologies. Instead, increasing experience through consistency plays a key role in reducing uncertainties. Third, I identify that uncertainty reduction treatments can interact positively or negatively. I outline three mechanisms: (1) Supportive, (2) Complementary, and (3) Competing.

Background and Hypothesis

Reducing Uncertainties Arising from Emerging Technologies

Rooted in Schumpeter's idea of creative destruction, emerging technologies and resulting innovations have been recognized as drivers for economic growth (Dosi, 1982). By definition (Rotolo et al., 2015), these technologies are prone to uncertainties (Rosenberg, 1996). Knight

(1921) described uncertainty as the lack of knowledge about the probability of an event happening, which distinguishes the concept from a risk where the probability distribution is known (Gomes et al., 2022). For companies in the context of emerging technologies, high uncertainty materializes through a lack of knowledge regarding the future development of the technology itself, its product market fit, the preferences of prospective users, the ecosystem of complementary actors and technologies, and the potential business model (Kapoor & Klueter, 2021). On the level of individuals, the uncertainty reduction theory postulates that high levels of uncertainty trigger information seeking (Berger & Calabrese, 1975). Similarly, companies strive to obtain information or increase adaptability to missing information.

For both information seeking and increasing adaptability, treatment strategies exist, which Arend (2024a) clustered in six "buckets": (1) Cooperation and diversification targets to uncover unknowns through entities outside the focal company, e.g., through portfolio expansions. (2) Discovery and search aim to obtain better knowledge through information gathering. (3) Experimentation and experience seek to reduce the unknown by actively trialing technologies and creating mental models. The philosophies of trial-and-error learning (Furr & Eisenhardt, 2021) and corporate venturing (Covin et al., 2021) are rooted here. (4) Adapting to outcomes through flexibility and robustness enables companies to prepare for specific events, while (5) social construction and preemption targets to actively influence actors and thereby make the knowable known by "forging" the future (Townsend et al., 2018). (6) Scenarios create information about what possibly could be.

Missing to address uncertainties by failing to apply treatment strategies bears risks. For example, companies could fail to identify chances for the technology in other applications or with different business models, neglect to help the technologies innovation ecosystem to develop, and misjudge the required resources to generate value (Kapoor & Klueter, 2020). This especially threatens incumbents (Amit & Zott, 2012; Snihur et al., 2018) since uncertainties require incumbents to "reconfigure their existing knowledge base or routines, and firms may vary in terms of their ability to reconfigure" (Eklund & Kapoor, 2019; Kapoor & Klueter, 2021). Successful uncertainty treatment should thus manifest in higher financial performance and, consequently, greater longevity.

Portfolio Diversification and Timing Strategies

Market and technology entries are paramount for most companies' growth and long-term existence (Markman et al., 2019). They are a prime example of diversification as an uncertainty treatment strategy; simultaneously, these technology entries increase flexibility and robustness by increasing the breadth of experiences. This is particularly relevant when larger established firms – inhibited from addressing uncertainty by strict routines – (Hage, 1980; O'Connor & Rice, 2013) invest in younger, proactive, and more flexible companies (Zahra, 2008).

Reducing uncertainties is a vital theme in technology entries (Zachary et al., 2015). Ozalp & Kretschmer (2019) argue that firms seek entry into a technology where they expect the highest profitability, which, in turn, depends on reducing uncertainties about the fit between the niche and firms' capabilities. Many factors influence this, which Zachary et al. (2015) grouped into Who (the entering player), Where (the space), What (the entry type), How (the strategy), and When (the entry timing). Which Markman et al. (2019) amended by: „Complements" (assisting elements, e.g., networks) and "Nonmarket Forces" (e.g., cultural background).

Among these, the entry timing is the most prominently researched question. Its academic discussion started with Lieberman & Montgomery's (1988) article on first-mover advantages (FMA). Later, researchers added perspectives on early movers, fast followers, and late movers (Cho et al., 1998; Kerin et al., 1992; M. B. Lieberman & Montgomery, 1998; Shamsie et al., 2003) as well as other classifications like creator, anticipator, and follower (Agarwal & Bayus, 2004). Despite a broad set of studies tackling the topic of entry timing, Zachary et al. (2015) pointed out that various problems (e.g., methodological issues, varying conceptual lenses, understanding of entry as an event and not a process, missing research on resource-capability mix) persist and hinder a complete understanding. Despite these deficiencies, research generally agrees that in many market conditions, early entrants have advantages over later entrants (Szymanski et al., 1995; Zachary et al., 2015). Agarwal & Bayus (2004), for instance, found a superior survival rate for the cohort of creators (companies entering before firm number take-off) over anticipators (entering between sales and firm number take-off), which in turn have higher (5-year) survival rates than followers (entering after the sales-take off). They depart from the view of a single first mover and group companies in these cohorts; the likelihood of survival within a cohort does not differ. However, like many others, their study focuses on survival rates (Agarwal, 1996; Agarwal et al., 2002; M. Lieberman, 2002) and cannot answer which entry timing performs best financially.

Early mover and creator benefits depend on various antecedents and contingencies, broadly clustered in industry conditions, product factors, and firm characteristics (Zachary et al., 2015). Many entry-timing studies, however, focus on analyzing specific influencing factors solely in one industry with a population of firms (Hawk & Pacheco-De-Almeida, 2013) or individual companies' success in specific entries. This led to a broad literature body and a high level of research maturity (Zachary et al., 2015), suggesting that a clear perspective on advantageous entry strategies exists. However, research results are often specific to certain industries and market settings (Hidding & Williams, 2003; M. Lieberman, 2002; López & Roberts, 2002; Makadok, 1998), and markets are in permanent change and thus create "empirical ambiguities" (Zachary et al., 2015). For example, creator survival benefits materialize across industries when looking at the connection of one firm entering one industry (Agarwal & Bayus, 2004), neglecting the effect that individual companies make entry decisions permanently and are thus less exposed to the success in one entry but the average success across the bouquet of entries. Hence, the perspective of large incumbents is missing. For them, it is relevant to answer how successful the portfolio of their technology entries is on average.

Researchers previously saw portfolio management strategies from a project selection perspective (Baker, 1974; Danila, 1989) and later encompassed the prioritization of product developments to tap into new markets (Cooper et al., 2000; Tatikonda, 1999). Portfolio management aims to maximize value under the limited availability of resources while aligning the portfolio with a company's strategic direction (Augusto Cauchick Miguel, 2008; Cooper et al., 1997). It comprises simple extensions of existing products and radical ones that tap into new markets (Clark & Wheelwright, 1993). Portfolio management and innovation strategies are intertwined and aim to increase companies' performance (Ouma & Kilika, 2018).

Calling for studying entry timing strategies on a technology entry portfolio level poses the consequential question of whether FMA mechanics change and creator strategies are also beneficial on this level. Creator and first mover advantages depend on pre-emption, i.e., gaining and guarding early and thus superior access to scarce resources, technological leadership, switching costs for buyers, network effects, and brand loyalty (M. B. Lieberman & Montgomery, 1998). On the other hand, creators face higher levels of uncertainty about whether the market or technology proliferates. Later entrants face lower benefits from pre-emption but also a lower uncertainty. Thus, it comes down to which effect is more substantial. Agarwal and Bayus (2004) discussed the dynamics of these effects in detail along individual firm entries. On the one hand, the portfolio is "only" an agglomeration of a multitude of these entries where companies recognize opportunities, gauge potential drawbacks (Dew, 2009; Read et al., 2009), and prioritize market entries under limited resources based on whether early mover advantages are defendable (Coeurderoy & Durand, 2004; Lévesque & Shepherd, 2004; M. B. Lieberman & Montgomery, 1998). On the other hand, learning effects from repeated entries and synergies between the entered technologies and existing capabilities might influence the capabilities of early entries to effectively reduce uncertainties.

Following this argumentation, companies should have a certain evenness in their entry timing decisions to study creator benefits on a portfolio level. Qualitative research suggests that companies deliberately select a portfolio timing strategy of either later (lower uncertainty, lower returns) or earlier (higher uncertainty, higher returns) entrants (Klingebiel & Joseph, 2016). For instance, companies can bet on a broad set of early entries, expecting only one to be successful enough to balance losses from the others, a strategy resembling that of venture capital (VC) funds.

Consequently, I argue that the advantage of the creator benefit should not be different between the portfolio and the individual entry view and thus hypothesize (see Figure B-10):

Hypothesis 1: *Portfolio-level "entry timing" strategies focusing on the earliest possible entry (creator investor strategy) will lead to higher firm performance compared to those focusing on a later entrance (anticipator and follower).*

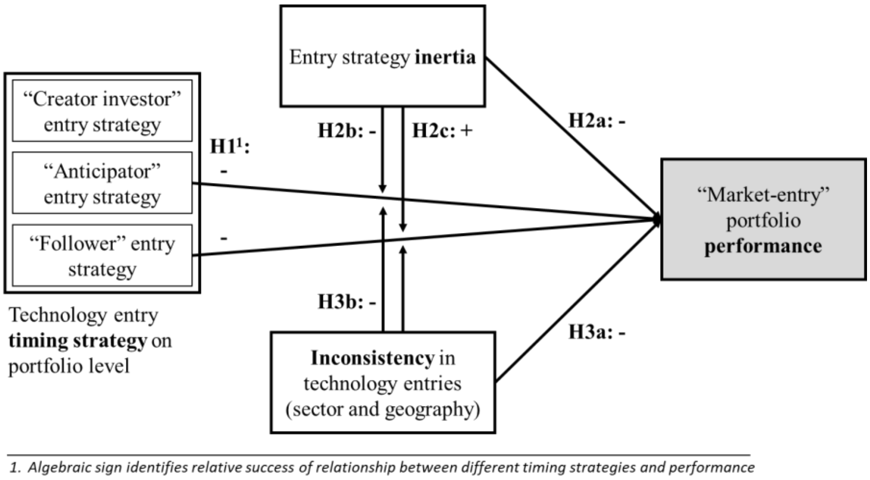


Figure B-10: Conceptual scheme for derived hypotheses

Interactions of Uncertainty Treatment Strategies

<u>Information-based strategizing in technology entries</u>

Strategic analysis acts as an early warning system, enabling firms to prepare and behave more effectively (Packard & Clark, 2020). Tackling uncertainties requires information, and this information-seeking leads to strategizing. When companies strategize, they are thinking about potential actions and possible outcomes, which are the foundation for making a decision on which option is the "best" to follow (Arend, 2024b).

The required information can be obtained via the aforementioned uncertainty reduction treatments. For example, companies gather information in technology entries by observing the behavior of competitors (Engel, 2010), which can lead to imitation when companies follow peers into new technologies (Cho et al., 1998; Haveman, 1993). This strategy reduces search costs (Cyert & March, 2006) because firms benefit from peers' prior risk assessments; it is observable in the VC industry (Sorenson & Stuart, 2008).

Even when search costs are reduced, companies spend valuable resources acquiring information. However, more information does not always lead to better strategies and higher returns. When information is scarce and short-lived, and subsequent analysis complicates the process, strategizing fails (Arend, 2024b) either because no reliable strategy can be created or it is already outdated at the time of creation (Marttila, 1999). This is especially the case in contexts where the potential cost of falling behind competitors surpasses the advantages of gathering additional information (Hertwig et al., 2019), as apparent in emerging technology entries. In this context, opportunistic company entry behavior can outperform companies following strategies deducted from ex-ante reasoning. Strategies created as adaptable "guides", accounting for changing circumstances, surprises, and new information to surface, will fare better (Ehrig & Schmidt, 2022). Consequently, the amount of strategic planning and adaptation must be tailored to the uncertainty involved in the entry decision (Packard & Clark, 2020).

By definition, emerging technologies are high-uncertainty environments that, according to Furr and Eisenhardt (2021, p. 1917), require „creating strategy by doing and thinking", while low-uncertainty environments require foresight and planning. The authors further highlight that acting flexibly in a "trial-and-error" manner is critical to success in these environments. Inflexibility to update the perspective on nascent technologies and the associated strategy can be a source of inertia (Furr, 2009), hindering economic success. Hence, I argue that high levels of strategy inertia (as the opposite of being flexible) have adverse effects on technology entry portfolio performance and hypothesize:

Hypothesis 2a: *High levels of strategy inertia negatively influence "market entry"-portfolio performance.*

My argument is that inflexibility and inertia in the strategizing process lead to less performance in a highly uncertain environment, which yields consequences for the relevance of inertia in the different timing strategies. Creator and anticipator timing strategies engage with emerging technologies earlier in their diffusion and must consequently deal with even higher uncertainties than follower strategies. Therefore, I argue that how companies approach uncertainty reduction through information gathering and analysis has not only an influence on the success of this treatment strategy itself but also on the interaction with the diversification method. I reason that companies that seek information too intensively and stick to pre-defined strategies rigorously perform worse in their diversification strategy when pursuing an anticipator strategy to reduce uncertainties. This is the case because, in early market timings (e.g., during anticipator strategies), there is information that is not (or only prohibitively expensively) attainable. Additionally, the market environment moves so quickly that strategies become outdated rather quickly. Consequently, I hypothesize:

Hypothesis 2b: *A high degree of strategy inertia negatively moderates the relationship between early timing (anticipator) strategies and performance.*

Conversely, companies' diversification strategies can benefit from extensive information seeking, planning, and rigorous execution (high strategy inertia) when uncertainties during the technology entry are lower and change slower, i.e., when companies pursue a follower strategy. The later entrance strategies give companies more time to gather information, build solid strategies, and make decisions. Additionally, later market timings allow information to be obtained with fewer resources, and the information to be outdated slower. For instance, sticking with a predefined strategy can prevent entries purely based on the "fear of missing out" effect – a standard scheme in technology entries – which diverts resources from other market entries with potentially higher returns (Güngör et al., 2022). Consequently, I hypothesize:

Hypothesis 2c: A high degree of strategy inertia positively moderates the relationship between late-timing (follower) strategies and performance.

<u>Consistency, a virtuous corrective</u>

Another treatment strategy for uncertainty is creating experience; it sets the frame for experimentation and is required for learning, generating hypotheses to test, and making sense of information (Arend, 2024a). People and organizations learn from experience to identify patterns by developing rules for interpreting clues and combining them to predict outcomes, which allows them to build flexible strategies based on specific examples (Hertwig et al., 2019; Medin & Schaffer, 1978). In the case of technology entry portfolios, diversification can also be seen as a sort of experimentation while the process, in any case, increases experience because it widens the breadth of trialed technologies. Contrarywise, this experience also influences diversification because it sets the frame for how information is acquired and processed and how decisions are made. Experience forms mental models, which are used as a structure to reason in uncertain environments, and relevant experience leads to better performance (Furr, 2019; Furr & Eisenhardt, 2021).

Hence, the experience can ensure that information is regularly processed and interpreted in new ways, which is critical to creating good trial-and-error strategies. Companies can even substitute information from search processes if they have past experiences in the market (Guillen, 2002; Simon & Lieberman, 2010). For example, in the VC context, experience (number of previously raised funds) can increase fund performance (Smith et al., 2011), and experienced firms can find valuable investment targets sooner, earning higher profits (De Clercq et al., 2001). Those insights are limited to "direct" experience in the market and explain success in re-entries.

However, per definition, emerging technologies are new, and re-entries are impossible, making experiences in the other connected uncertainty dimensions (business model, application, ecosystem, user) more relevant. Companies reduce entry uncertainties by entering technologies in geographic or sectorial markets they know well (Hilmersson & Jansson, 2012; Lamperti et al., 2020; M. B. Lieberman & Asaba, 2006). In sectorial and geographic markets, ecosystems exist that companies know well, possible applications are close, and potential users who might be willing to engage with certain business models are easier to identify. Thus, consistency in sectors and geographies when entering emerging technologies reduces the associated "non-technology" uncertainties. Van den Hoed (2007) highlighted that local market factors play minor roles in the commercialization of emerging technologies, and Fatima (2017) found that these technologies tend to be global phenomena, i.e., embedded in global research networks and supply chains. This leads to the conclusion that sectorial experience may be more relevant for determining entry success in emerging technologies.

Experience can be gained and leveraged by consistently making technology entries in specific regions or industries. Consistency eases the identification of obstructions and opportunities (Kisunko et al., 1999). I argue that inconsistent companies have lower information and thus face higher uncertainty, ultimately reducing performance. I hypothesize:

Hypothesis 3a: *High levels of entry inconsistency – both on sectors and geographies – negatively influence "market entry"-portfolio performance.*

In so far, I believe that experience is the better treatment in areas with very high uncertainty. Contrary to the case of strategy inertia, I argue that there is no adverse effect from having "too much" experience. Reducing inconsistencies to reduce uncertainties in technology entries is thus promising, independent of the timing strategy. I hypothesize:

Hypothesis 3b: *A high degree of inconsistency – both on sectors and geographies – negatively moderates the relationship between entry timing strategies (anticipator, follower) and performance.*

Data, Method, and Model

Empirical Setting

The entry research often examines product launches from corporate R&D departments (Zachary et al., 2015). But, companies increasingly pursue alliances, joint ventures, as well as mergers and acquisitions to gain market access (Das & Teng, 1999; Schildt et al., 2005; Teng, 2007). Taking minority stakes in startups via corporate venture capital (CVC) outfits became another option to obtain access to capabilities (Chesbrough, 2002; Dushnitsky, 2008; Gompers & Lerner, 2004). It is specifically aimed at new technologies in the early phase of market development (Dushnitsky, 2008) because Startups are "important originators of innovations"

(Kim & Park, 2017, p. 161). CVC investments increase economic performance, innovation rates, and sensitivity to identify technological disruptions (Dushnitsky & Lenox, 2006; Maula et al., 2013; Wadhwa & Kotha, 2006) but also form a way to manage a company's technology portfolio (Fayolle & Lipuma, 2011) when high uncertainty is prevalent (Kim & Park, 2017; Maula et al., 2013). Together, startups and their backers form the ecosystem for new technologies to proliferate (Gompers & Lerner, 2001) and constitute the early phase of evolving markets. They are ideal for studying entry strategies (e.g., Makarevich & Kim, 2019).

Hence, my analysis uses the venture capital (VC) industry as a proxy to analyze my research questions. I follow other researchers studying market entry dynamics in this context (Makarevich & Kim, 2019) who highlighted multiple reasons why the industry is suitable as a proxy. VC's operating model is identifying promising new technologies and markets to enter with the goal of financial profit from entry decisions (Gompers & Lerner, 2004). This isolates entry decision performance from other factors of influence. They also permanently chose between staying in known and entering new markets (Cheng, 2012). Additionally, the industry is tracked in databases with high data quality (Retterath & Braun, 2020). VCs perform entries often (Podolny, 2001). Similar to incumbents, VCs influence the development of their portfolio companies (Gao, 2011) and typically have sector-specific knowledge (Dimov & Martin de Holan, 2010). They strategize resulting in information about their target markets. Finally, different VC portfolios' performance can be compared easily via internal rates of returns (IRR).

Data

I used PitchBook as a data source[6], which has been collecting startup and investment data since 2007 and contains data on more than 712k VC investments. The platform is reliable for the startup and venture capital ecosystem (Kaplan & Lerner, 2017; Retterath & Braun, 2020). Data can be analyzed and downloaded on multiple levels (investor, fund, portfolio company, and deal level). Matching between the different levels is reliable due to unique IDs.

I downloaded VC fund-level data to run dedicated analyses on a fund's performance. Since I was interested in viewing the entirety of a fund's timing strategies, I could only look at liquidated or fully invested funds[7]. I filtered all funds (ca. 2300) to include only those fulfilling these criteria and which have tracked performance data[8]. This resulted in 888 fund data records, which I then downloaded. I limited my search to VCs with headquarters in North America (788)

6 Official Pitchbook Disclaimer: Analyses are based on self-conducted platform searches. Neither the method nor the data has been reviewed by PitchBook analysts. The usage of the data was granted for this research project only.
7 No evergreen, currently raising, or open funds are included.
8 Limited partners (LPs) of the respective funds report the performance data. LP investors invest their money in VC funds. They have limited liability and are not involved in the day-to-day management of the fund. This makes LP-reported performance data reliable but prone to missing data. Using this kind of data can underly potential selection biases (Smith et al., 2011).

and Europe (100). The vintage years are between 1979 and 2022 (average 2003), a time when US investors dominated the VC market (Aizenman & Kendall, 2011). The VCs are a cross-industry sample; the average fund size is 167 USDmn. Two-thirds are general VC funds, 25% early-stage, and less than 5% late-stage funds. I also downloaded the deal records (194k data points) to create the independent variables and matched them with the fund data (see next below). This decreased the sample size to 386[9] funds due to missing data. All data wrangling was done in Tableau Prep Builder® and R, and the statistical analyses were run in Stata®.

Measures and Analysis

Dependent variable

Performance. Entry-timing researchers have long called for metrics other than survival rates and market shares to be used to study FMAs, especially looking at profitability (Agarwal & Bayus, 2004). Following Smith et al. (2011), I used a fund's internal rate of return (IRR) as a performance metric and dependent variable[10]. The IRR is a commonly used measure of profitability, it is the discount rate that sets the Net Present Value (NPV) of a series of cash flows to zero, assuming at least one positive and one negative cash flow (Mellichamp, 2017).

Independent variables

Strategy inertia. I operationalized the strategy inertia variable by comparing whether funds made their investments in sectors (defined by PitchBook), verticals (emerging technologies), investment types (defined by PitchBook), and geographical regions (defined by PitchBook) they stated to be their investment preferences[11]. As described in the "Background" section, strategy inertia measures inflexibility in strategic planning and extensive information gathering.

$$SL_i = \frac{\sum_{ij} d_{ijp}}{\sum_{ij} d_{ij}}$$

Where SL = Strategy Inertia, i denotes the funds, j denotes the deals, d stands for deals, and p denotes if a deal fulfils a fund-stated preferences

Inconsistency. A fund's inconsistency is operationalized by calculating the Euclidian distance between a vector containing the fund's investment behavior (within a sector or region) and a vector tracking the investment behavior of the fund's general partner[12] (across all its funds) in the five years before a funds vintage. I followed Makarevich & Kim (2019) by making

9 I calculated a paired T-test between our subsample and the remaining data to analyze the mean difference for each variable. I found mean differences for half of the variables. The dependent variable shows significant ($p<0.05$) differences. Where our subsample shows a 5.292%p lower mean IRR.

10 Measured at the end of a fund's lifetime for liquidated funds and the latest available date for fully-invested ones.

11 PitchBook sources the investor preferences based on "what is stated on investor or fund websites alongside information gathered directly from the investors or funds themselves," according to their platform FAQ.

12 A general partner is a managing partner of a VC fund, which is responsible for managing it and making investment decisions.

variables associated with experience time-dependent in a five-year horizon to account for the changing knowledge of the deal makers at the respective investor companies. I calculated the inconsistency separately for the sectorial and regional dimensions to create two inconsistency measures. I logarithmised each value to achieve a normal distribution and prevent a non-normal distribution of residuals in my model (see “Model” section). As described in the “Background” section, inconsistency measures how much experience can be gathered in non-technology uncertainty dimensions and, thus, a proxy for how well companies reduce those.

$$IC_{Ver,i} = \ln\|p_i - q_y\| \ where \ p_i = \begin{matrix} \sum_{ij} d_{ijk_1} \\ \sum_{ij} d_{ijk_2} \\ \sum_{ij} d_{ijk_n} \end{matrix} \ and \ q_y = \begin{matrix} \sum_{yj} d_{yjk_1} \\ \sum_{yj} d_{yjk_2} \\ \sum_{yj} d_{yjk_n} \end{matrix}$$

Exemplary for verticals: Where IC = Inconsistency, i denotes the funds, p is a vector containing a sum of the deals j a fund made in a vertical category k, q is a vector containing a sum of the deals j an investor y made in a vertical category k in the five years prior to a funds vintage

Entry timing. Traditionally, one would classify entries as first movers, fast followers, and late followers. However, there is only one – often hard to identify – first mover and the latter two groups are not objectively distinguishable, having been categorized differently in the past (Von Fischer et al., 2007). For the market entry timing, I looked at the PitchBook’s “Verticals”, which provide a good ground for analyzing entries because they are 1) “designed to slice across industries such that a single vertical may comprise companies spanning multiple industries” (according to the PitchBook FAQ) and 2) comprise of emerging technologies (e.g., 3D printing, Artificial Intelligence, Autonomous Cars, Robotics, and Drones). There are 58 PitchBook-defined verticals in the data set. Manually classifying periods to distinguish the three traditional categories for each vertical is neither possible nor desirable. I thus leaned on the logic of Agarwal & Bayus (2004), who classified firms as *creators, anticipators*, and *followers*.

Since the logic was defined for individual firms’ entries, I aimed to convert the concept to make it applicable in my setting. I pulled data from PitchBook showing the development of VC deals per vertical over time. Since the VC industry grew over the decades, trends that beat overall deal growth are not becoming evident from viewing deal counts (all curves rise). To tackle this issue, I calculated and then plotted the component of the annual share of deal counts per vertical, which was above or below the average annual share of deal count for all deals.

$$S_{v,t} = S_{tot,v,t} - S_{avg,t} \ where \ S_{tot,v,t} = \frac{\sum_{vtj} d_{vtj}}{\sum_{vj} d_{vj}} \ and \ S_{avg,t} = \frac{\sum_{tj} d_{tj}}{\sum_{j} d_{j}}$$

Where S = Annual share, j denotes the deals, d stands for deals, v denotes verticals, t denotes a specific year

To classify the timing strategy, I leaned on Golder & Tellis' (1997) and Agarwal & Bayus' (2004) method of using markers to distinguish categories (*creator investor, anticipator, follower*). Figure B-11 shows my procedure exemplary for the vertical "CleanTech". I classified all deals between the first positive value (stronger growth than average VC market determining the firm-take-off) and the maximum value as *anticipators*; all deals between the peak and the last[13] positive (before returning to a growth rate equivalent to deals in the entire VC industry) value as *followers*. The entries two[14] years before the first positive value were classified as *creator investments* (entry before firm take-off). I deviated from the classification of Agarwal & Bayus (2004), who used the sales take-off as a demarcation to distinguish *anticipators* and *followers*. However, reliable sales data cannot be obtained for all verticals, so I decided to settle on the peak point (highest company growth rate) as a demarcation. My analysis thus neglects deals outside the area marked in "grey" (Figure B-11). Based on this classification of fund deals, I then calculated three variables to mark the entry timing strategies. Each holds the share of deals a fund made in this category across all verticals the fund invested in. Hence, the sum of them always equals 1 for each fund.

$$E_{i,creator} = \frac{\sum_{ij} d_{ij,creator}}{\sum_{ij} d_{ij}} \text{ and } E_{i,anticip} = \frac{\sum_{ij} d_{ij,anticip}}{\sum_{ij} d_{ij}} \text{ and } E_{i,follower} = \frac{\sum_{ij} d_{ij,follower}}{\sum_{ij} d_{ij}}$$

Where E = Share of creator/anticipator/follower deals, i denotes the funds, j denotes the deals, d stands for deals, creator/anticipator/follower classifies whether a deal falls in this category

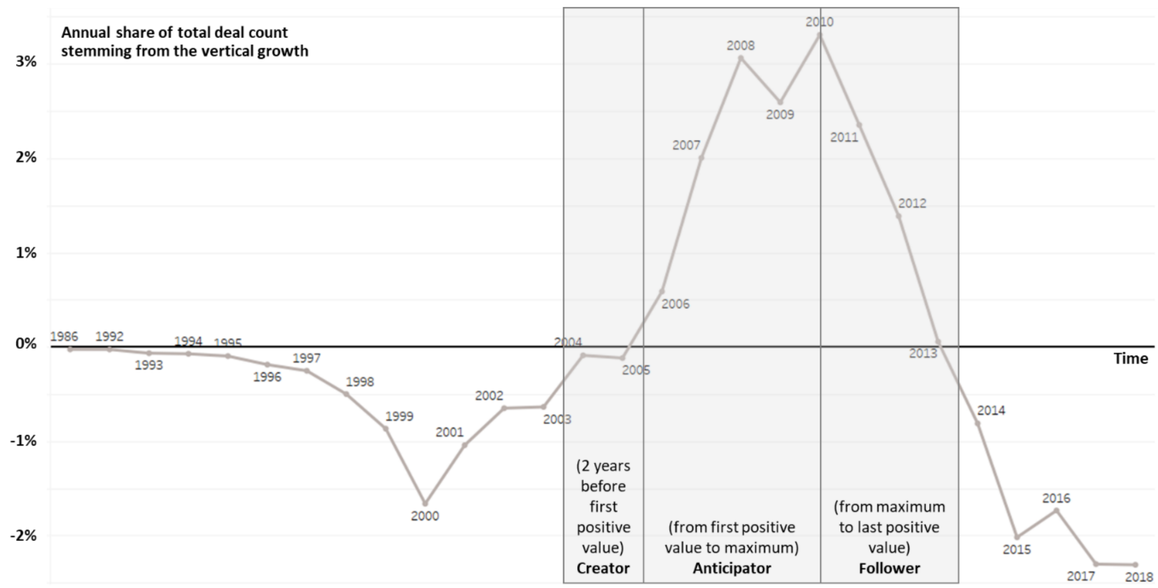


Figure B-11: Procedure to classify the entry strategies (Exemplary for the vertical "CleanTech")

13 Similar to reasoning for the demarcation of the creator investors (see next footnote), I ran a robustness check for the demarcating endpoint for the followers (see "Robustness check"-section).

14 I settled on two years due to the average length of the "hypes" within the verticals. Two years can already be a long period in terms of technological developments, but I aimed to capture the earliest movers in a field who are not just investing by chance. I acknowledge that this approach takes the risk of using a seemingly arbitrary time frame which is why I ran a robustness check on this assumption (see "Robustness check"-section).

Controls

The VC industry is rich in quantitative studies identifying performance-influencing factors (Cheng, 2012; Gompers et al., 2009; Söderblom & Wiklund, 2006), which require controlling.

Vintage year. Following Smith et al. (2011), I controlled for the vintage (year a fund was issued) since VC funds' performance depends on the overall economic development (Kwak, 2020). I clustered the vintage years in 5-year buckets and used them as categorical variables.

Fund type and sector specialization. Prior research (Gompers et al., 2009) shows that fund performance depends on a fund's investment in specific investment series sectors. Therefore, I introduced two categorical variables (fixed effects) identifying which investment type (Late-stage, Early-Stage, Venture-General, Angel) and which sector (derived from PitchBook, e.g., Consumer, Energy, Information Technology, etc.) a fund primarily invests in.

Syndication share. Makarevich & Kim (2019) argue that networks and partners reduce uncertainties in entry decision processes by obtaining information through their network. Cheng (2012) uses venture capitalists' syndication behavior as a proxy for the network ties influencing market entry. Up to 90% of deals come through VC networks (Gompers et al., 2020), and high syndication rates lead to better VC fund performance (Söderblom & Wiklund, 2006). I, therefore, controlled for this fact by using a variable indicating the share a VC fund invests in in a syndicated (together with other VC funds) manner.

Difference in location between fund and portfolio company. Chen et al. (2010) shed light on the role of geographies in the VC industry and point out that the difference between an investor's and its portfolio company's geographic location influences performance. To account for this, I introduced a variable measuring the share of deals a given investor does outside its "home" region compared to the total deal amount.

Next to these, I control for four other fund-specific characteristics. The ***fund size*** influences fund performance (Söderblom & Wiklund, 2006). I use it as an absolute value, which I logarithmized to achieve a normal distribution (there tends to be a significantly greater number of smaller funds than bigger ones). I also control for the influence of the ***average holding time of a portfolio company*** (Söderblom & Wiklund, 2006), a variable I assigned with the average time between the first investment in a portfolio company and the fund's exit. Additionally, I controlled for the average ***allocation duration of a fund***, meaning the time between the first investment of a fund and the last investment in a new portfolio company (reinvestments excluded). Lastly, I controlled the ***reinvestment rate,*** the share of investments going to portfolio companies that have already received investments.

Model

My model aims to connect performance measured in IRR and various independent variables. Since performance is a continuous variable without natural boundaries, I chose a standard OLS (ordinary least squares) regression (Burton, 2021). I first built models to evaluate the direct effects of the independent variables and then continued to test the moderation effects (see Table B-12). I tested each model's base assumption for linear regressions (Marill, 2004), assessed the collinearity through the correlation matrix (see Table B-11) and calculated "variance inflation factors". To prevent collinearity in models that use the three timing variables, I omitted the *creator investors* variable from the model. The three variables defining the market entry strategy show linear correlations (coef. = -0.912; 0.14; -0.54). By definition, this must be the case because all three sum up to 100% for each fund and are thus a linear combination (see "Method" section). Omitting one variable results in a relative interpretability[15] for the remaining *anticipator* and *follower* variables. Additionally, we find a linear correlation (coef. = 0.66) between the "Location difference share" and the "regional inconsistency"[16]. We address this by controlling the variance inflation factors for each model and checking the omittance of the location difference (see "Robustness Check").

Lastly, I clustered the standard errors based on a variable identifying the investor to which a fund belongs to prevent heteroskedasticity and removed outliers[17] to ensure normally distributed residuals. I tested the heteroskedasticity with the Shapiro-Wilk test and visual analysis of the plotting of quantiles of the residuals against the quantiles of normal distribution. Additionally, I standardized all continuous variables before calculating the model results.

Results

I present the descriptive summary statistics and the bi-variate correlation analysis of all described variables in Table B-11 and the results of the regression models in Table B-12. Model 1 includes only the control variables' influence on fund performance, while Models 2 to 4b represent models that investigate the direct effects of all independent variables separately. Models 5a to 6b add the respective moderating effect between the independent and entry timing variables. Building on this, Models 7a (sector inconsistency) and 7b (regional inconsistency) are the full models, including all variables to test my hypotheses. Since Model 7b fails to show significant influences, I describe Model 7a in detail and highlight the differences between the two models.

[15] For instance, negative coefficients indicate that those strategies lead to less performance than the creator strategy.
[16] This is only relevant for those models that include "regional inconsistency".
[17] Outlier removal did not change the expression, i.e., no change in significance, magnitude, and sign of the coefficient.

Variable	N	Mean	STD	Min	Max	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
(1) Performance (IRR, %)	386	8.71	16.17	-38.6	67.5	1												
(2) Follower share (%)	386	.25	.19	0	.9	.23	1											
(3) Anticipator share (%)	386	.66	.23	.08	.98	-.36	-.91[2]	1										
(4) Creator inv. share (%)	302	.12	.09	0	.48	.38	.14	-.54	1									
(5) Sector inconsistency[1]	386	.46	.38	.01	1.76	-.02	-.10	.07	-.05	1								
(6) Region inconsistency[1]	256	.19	.28	0	1.41	.23	.18	-.23	.22	.06	1							
(7) Strategy inertia (%)	386	.48	.25	0	.93	-.33	-.26	.34	-.27	-.24	-.20	1						
(8) Location diff. share (%)	386	.11	.17	0	.92	.15	.07	-.10	.15	.04	.66[3]	-.09	1					
(9) Allocation duration (Y)	386	6.6	3.38	1	19	-.09	.06	.00	-.19	-.10	-.09	.10	-.06	1				
(10) Fund size (USDmn)[1]	386	215.8	275.8	.54	1866	-.26	-.24	.31	-.25	-.14	-.11	.44	.07	.13	1			
(11) Avg. holding time (Y)	386	4.88	1.69	.67	12.5	-.38	-.29	.37	-.33	.08	-.17	.23	-.09	.10	.11	1		
(12) Reinvestment rate (%)	386	.37	.16	.02	.9	-.17	-.11	.11	-.03	-.16	-.13	.21	-.05	.09	.26	.17	1	
(13) Syndication share (%)	386	.9	.12	.21	1	-.04	-.16	.18	-.12	.00	-.14	.12	-.11	.01	.28	.03	.33	1

Variable	N	%	cum
Vintage year	386		
2000-2004	108	27.98	27.98
2005-2009	103	26.68	54.66
2010-2014	77	19.95	74.61
2015-x	62	16.06	90.67
x-1999	36	9.33	100
Sector specialization	386		
Business Products and Services (B2B)	7	1.81	1.81
Consumer Products and Services (B2C)	17	4.40	6.22
Energy	3	0.78	6.99
Healthcare	95	24.61	31.61
Information Technology	255	66.06	97.67
Multiple Sectors	9	2.33	100
Fund type	386		
Venture - General	237	61.40	61.40
Venture - Early Stage	126	32.64	94.04
Venture - Later Stage	23	5.96	100

All coefficients <-0.1 and >0.1 are significant, at least at the 0.05 level. We report coefficients based on unstandardized data.
1: This variable was logarithmised before calculating the pairwise correlation matrix.
2: Variables in this box sum up to 1 for each fund and are thus, by definition, co-variate. Hence, one variable will always be omitted in analysis to prevent co-variance in the model.
3: Co-variance between location difference share and region inconsistency will be treated in "robustness check"-section.

Table B-11: Descriptive statistics and pairwise correlations

		Controls		Direct effects				Moderated effects			Full model	
Group	**Variables**	**M1**	**M2**	**M3**	**M4a**	**M4b**	**M5a**	**M5b**	**M6a**	**M6b**	**M7a**	**M7b**
Direct effects	*(2) Follower share (%)*		-6.897***				-6.714***	-5.902**	-8.852***	-5.208*	**-9.78*** **	-5.285
			(2.384)				(2.379)	(2.462)	(2.571)	(3.108)	**(2.805)**	(3.319)
	(3) Anticipator sh. (%)		-7.139***				-7.024***	-6.191**	-8.395***	-4.779	**-9.368*** **	-4.684
			(2.445)				(2.463)	(2.501)	(2.578)	(3.233)	**(2.784)**	(3.491)
	(4) Creator inv. sh. (%)[2]		*Omitted*	*Omitted*	*Omitted*	*Omitted*	*Omitted*	*Omitted*	*Omitted*	*Omitted*	***Omitted***	*Omitted*
	(5) Sector inconsistency[1]				-1.004				-3.641***		**-4.814*** **	
					(.758)				(1.202)		**(1.292)**	
	(6) Region inconsis.[1]					1.993				2.663		2.438
						(1.263)				(2.543)		(2.427)
	(7) Strategy inertia (%)			-1.565*			-3.195***	-1.355			**-5.363*** **	-2.346
				(.917)			(1.108)	(.909)			**(1.783)**	(2.325)
Moderated effects	*(2) x (5)*								-5.113***		**-5.464*** **	
									(1.762)		**(1.951)**	
	(3) x (5)								-3.887**		**-4.572** **	
									(1.723)		**(1.766)**	
	(2) x (6)									1.382		2.118
										(3.249)		(2.988)
	(3) x (6)									1.679		1.554
										(2.775)		(2.65)
	(2) x (7)							2.331**			**-2.559**	2.612
								(1.142)			**(2.497)**	(2.631)
	(3) x (7)						-2.621**				**-4.612** **	-1.428
							(1.063)				**(2.188)**	(2.798)
Controls	*(9) Location diff. sh. (%)*	1.649**	1.713**	1.557**	1.714**	.465	1.503*	1.535**	1.791**	.847	**1.559***	.791
		(.818)	(.809)	(.788)	(.832)	(1.137)	(.767)	(.763)	(.831)	(1.164)	**(.798)**	(1.157)
	(10) Alloc. duration (Y)	.262	.285	.247	.244	.446	.14	.22	.286	.436	**.085**	.462
		(.632)	(.637)	(.63)	(.632)	(.689)	(.632)	(.629)	(.635)	(.706)	**(.627)**	(.697)
	(11) Fund size (USDmn)[1]	-1.609*	-1.575*	-1.172	-1.782*	-.891	-1.281	-1.265	-1.786*	-1.041	**-1.394**	-1.207
		(.889)	(.875)	(.892)	(.92)	(.863)	(.856)	(.862)	(.909)	(.893)	**(.873)**	(.871)
	(12) Avg. holding t. (Y)	-3.078**	-3.115**	-3.131**	-3.082**	-1.963	-3.263**	-3.224**	-3.107**	-2.417	**-3.231** **	-2.541
		(1.37)	(1.373)	(1.371)	(1.379)	(2.051)	(1.314)	(1.334)	(1.372)	(2.062)	**(1.326)**	(1.974)
	(13) Reinvest. rate (%)	-.795	-1.162	-.73	-.933	-1.459	-.693	-.819	-1.292	-1.765	**-.91**	-1.617
		(.937)	(.908)	(.941)	(.923)	(1.353)	(.922)	(.911)	(.897)	(1.319)	**(.904)**	(1.307)
	(14) Synd. share (%)	1.705	1.888*	1.614	1.838*	1.694	1.724*	1.767*	1.828*	1.847	**1.646**	1.966
		(1.046)	(1.056)	(1.031)	(1.057)	(1.272)	(1.019)	(1.021)	(1.069)	(1.282)	**(1.04)**	(1.212)
	Constants	2.877	.582	3.145	4.111	3.494	2.135	2.258	1.174	1.594	**3.279**	3.131
		(4.472)	(4.762)	(4.398)	(4.646)	(4.511)	(4.563)	(4.566)	(5.004)	(4.843)	**(4.824)**	(4.578)
	Year dummy	YES	YES	YES	YES	YES	YES	YES	YES	YES	**YES**	YES
	Sec. spec. dummy	YES	YES	YES	YES	YES	YES	YES	YES	YES	**YES**	YES
	Fund type dummy	YES	YES	YES	YES	YES	YES	YES	YES	YES	**YES**	YES
General	*Observations*	386	386	386	386	256	386	386	386	256	**386**	256
	R-squared	.342	.358	.347	.344	.367	.375	.372	.374	.375	**.396**	.4
	VIF average	2.88	3.75	2.83	2.87	2.71	3.61	3.56	4.24	4.34	**4.79**	4.62
	Prob>z Shapiro-Wilk	.469	.779	.344	.266	.203	.626	.477	.382	.245	**.316**	.339

Standard errors are in parentheses *** $p<.01$, ** $p<.05$, * $p<.1$ *1: This variable was logarithmized before calculating the pairwise correlation matrix. 2: Omitted due to linear dependence on (1) and (2). The model highlighted in bold is described in the text in detail. All models are calculated with clustered standard errors.*

Table B-12: Overview of model results

Direct effects

I started by looking at the variables on market entry to analyze the main effect of H1, where I assumed that portfolio-level "entry timing" strategies focusing on the earliest possible entry (*creator investor* strategy) would lead to higher firm performance compared to those focusing on the later entrance (*anticipator* and *follower*). Both the *follower* (coef. = -9.78, $p < 0.01$) and the *anticipator* (coef. = -9.37, $p < 0.01$) variables are significant, and the coefficients are negative, which means that the *creator investor* strategy is dominant. This, in turn, lends support to H1; I can confirm that a FMA on a portfolio level exists.

Looking at the effect sizes, I can see that the *anticipator* strategy yields better results than the *follower* strategy. A one standard deviation increase of the anticipator share (23%p) leads to a 9.37%p lower IRR, which would lead to a ~294 USDmn average loss in returns over ten years for the average fund, which usually wreaks in 280 USDmn totally over this period. For the *follower* strategy, one standard deviation (19%p) decrease would equal a 9.78%p higher IRR, totaling ~303 USDmn loss in ten years. Both effects are bigger than of all other variables. The results remain similar across all models except for 6b and 7b, where the smaller sample size – due to missing data in *regional inconsistency* – might explain the deviation.

In H2a, I assumed that high levels of strategy inertia negatively influence "market entry"-portfolio performance. I found a significant negative influence of strategy inertia (coef. = -5.36, $p < 0.01$) on fund performance. One deviation higher inertia decreases the IRR by 5.36%p (~197 USDmn over ten years for average fund). This is the third most potent direct effect. The effect also remains largely stable across the models. Thus, H2a is supported.

I split the models 7a to 7b along the inconsistency per each level of analysis (region, sector). I could only find a significant direct effect for the sectorial inconsistency (coef. = -4.81, $p < 0.01$), where high values (high Euclidian distance) indeed lead to lower performance. One deviation higher inconsistency thus decreases the IRR by 4.81%p (~180 USDmn over ten years for average fund), rendering it the weakest direct effect. In H3a, I assumed high levels of entry inconsistency negatively influence "market entry"-portfolio performance. My results support H3a regarding sectorial inconsistency, but I found no evidence for the regional dimension.

Moderations

For the moderating effects, I modeled the interaction between the independent and market entry variables. I can show that strategy inertia's moderating influence on anticipator strategies' success is significant and stable across models. Even though I can see a significant moderation (coef. = 2.33, $p < 0.05$) of the *follower* strategy's success by the strategy inertia in the partial model (M5b), it does not persist in the full model (coef. = -2.56, $p > 0.1$). I cannot find support for H2c, where I assumed the relationship between late timing (*follower*) strategies and performance is positively moderated by a high strategy inertia.

In M7a, the interaction term between "anticipator share" and "strategy inertia" is negative (coef. = -4.61, $p < 0.05$). By looking at the associated margin plots (see Figure B-12), I can conclude that for an "anticipator" strategy, a high level of strategy inertia reinforces the existing negative effect. At high inertia, the performance drops from 13% at no anticipator share to -12% of high anticipator share, marking a 25%p drop in IRR. While at no inertia, the performance only drops from 14% at no anticipator share to 7% at a high anticipator share, marking only a 7%p drop in expected IRR. Sticking with priorly defined strategies while trying to anticipate (fast follow) new technologies has a punishing effect. This supports H2b, where I assumed that a high level of strategy inertia negatively moderates the relationship between early timing (anticipator) strategies and performance.

Looking at the interaction between inconsistency and timing strategies, I split the model to show the moderating effect for each category of inconsistency. I only see a significant interaction between the entry strategy variables and the sectorial inconsistency, where both coefficients are negative (coef. = -5.64, $p < 0.01$ and coef. = -4.57, $p < 0.05$). Their effect strength is comparable to those of the other significant moderating effects. I look at the margin plots in Figure B-13 (Part A and B) to investigate the relation.

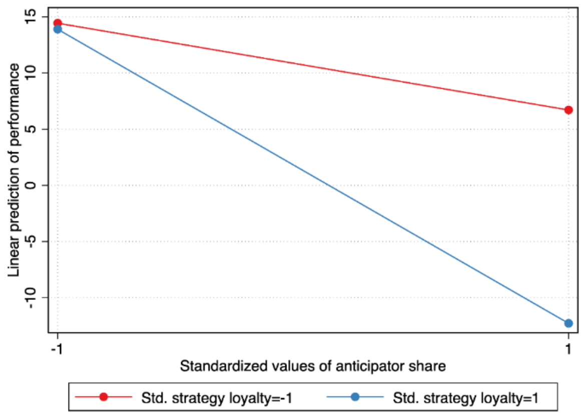
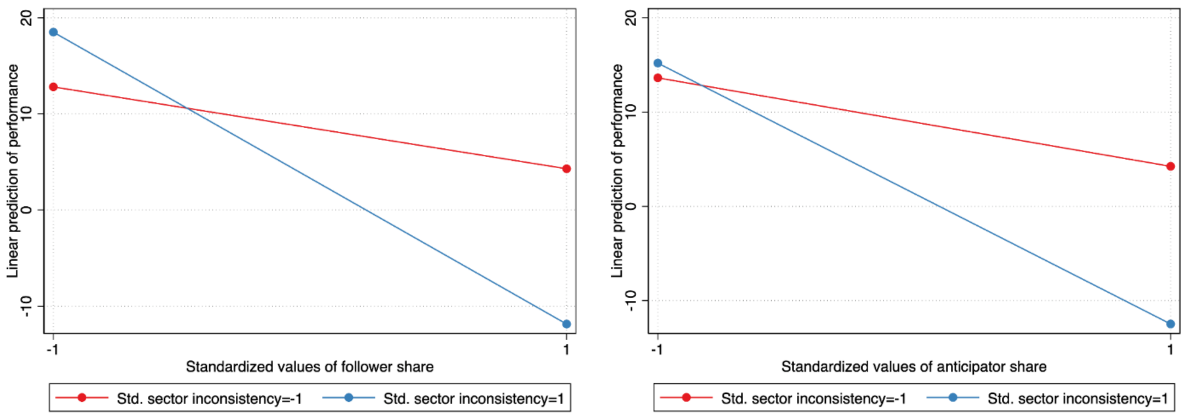


Figure B-12: Interaction of anticipator share and strategy inertia (Margins plot of Model 7a)

The plots for both *anticipator* and *follower* look similar and suggest that a low sectoral inconsistency mitigates the negative effect of entering "too late ". In both cases, the effect size is quite similar, dropping by ~25%p in the case of high inconsistency and only by ~7%p in the case of low inconsistency. Thus, being more consistent prevents a ~18%p steeper drop than being inconsistent. This finding supports H3b but only for the sectorial dimensions, where I assumed that the relationship between entry timing strategies (*anticipator, follower*) and performance is negatively moderated by an inconsistency. I find no evidence for H3b holding for the regional dimension.

In this study design, the margin plots compare to the omitted variable *creator investor* share due to its linear dependence on the *anticipator* and *follower* share. Considering this, I tested whether the two blue and red lines of Part A and B in Figure B-13 are significantly different. I can accept the null hypothesis, with the effects (Prob > F = 0.72 and 0.47) being equal across the *anticipator* and *follower* shares. Thus, the moderating effects between entry strategy and inconsistency do not differ for the two entry strategies.



Part A Part B

Figure B-13: Interactions of entry strategies and sector inconsistency (Margins plots of Model 7a)

Robustness Check

As mentioned in footnotes 9 and 10, I ran robustness checks for the periods defining the *creator* and *follower* cohorts. I ran this check on Model 7a; Table B-13 shows the results. I calculated the models ceteris paribus and only changed the defining periods. First, I extended the *follower* period to encompass all years after the maximum of the curve shown in Figure B-11. Second, I limited the *creator* period to one year before the first positive value of the curve, third to three years, and fifth to five years. The results do not change majorly; the direct effects, the controls, and most moderations are qualitatively unaffected. Only the moderating effect between the anticipator share and the sector inconsistency loses significance in the two variations. The results strengthen my procedure, as shown in the "Measures and Analysis" section.

Running the second robustness check also reveals no qualitative differences in the models. Here, I assessed the effect of omitting the "location difference share" variable from Model 7b based on the linear correlation between this variable and the regional inconsistency highlighted in the "descriptive statistics" section.

		Based on Model 7a					Based on M7b	
		Follower	Creator investor					
Group	Variables	ALL	1Y	2Y (std.)	3Y	5Y	Std.	Check
Direct effects	*(2) Follower share (%)*	-13.1***	-11.3***	-9.8***	-9.3***	-7.4***	-5.3	-5
		(3.7)	(3.2)	(2.8)	(2.2)	(1.8)	(3.3)	(3.3)
	(3) Anticipator sh. (%)	-12.9***	-10.3***	-9.4***	-8.6***	-6.9***	-4.7	-4.3
		(3.8)	(3.2)	(2.8)	(2.4)	(1.8)	(3.5)	(3.4)
	(4) Creator inv. sh. (%)[2]	*omitted*	*omitted*	*omitted*	*omitted*	*omitted*	*omitted*	*omitted*
	(5) Sector inconsistency[1]	-4.8***	-4.8***	-4.8***	-4.8***	-4.1***		
		(1.8)	(1.5)	(1.3)	(1.1)	(1)		
	(7) Region inconsis.[1]						2.4	2.9
							(2.4)	(2.2)
	(8) Strategy inertia (%)	-4.3**	-5.5***	-5.4***	-4.3***	-4.2***	-2.3	-2.3
		(2.2)	(2)	(1.8)	(1.6)	(1.4)	(2.3)	(2.3)
Moderated effects	*(3) x (8)*	-6.4**	-4.4**	-4.6**	-5.4***	-4.6***	-1.4	-1.4
		(2.9)	(2.2)	(1.8)	(1.4)	(1.3)	(2.8)	(2.8)
	(2) x (8)	-.7	-2.5	-2.6	-1.1	-1	2.6	2.7
		(3.2)	(2.8)	(2.5)	(2.2)	(1.8)	(2.6)	(2.6)
	(2) x (5)	-6.9**	-5.5**	-5.5***	-6.2***	-5.6***		
		(2.9)	(2.3)	(2)	(1.6)	(1.4)		
	(3) x (5)	-3.1	-4.6*	-4.6**	-3.1	-3.2**		
		(3)	(2.5)	(2.2)	(1.9)	(1.6)		
	(2) x (7)						2.1	2
							(3)	(3)
	(3) x (7)						1.6	1.4
							(2.7)	(2.7)
Controls	*(9) Location diff. sh. (%)*	1.5**	1.5*	1.6*	1.7**	1.7**	.8	
		(.8)	(.8)	(.8)	(.8)	(.8)	(1.2)	
	(10) Alloc. duration (Y)	.7	0	.1	0	-.1	.5	.4
		(1)	(.6)	(.6)	(.6)	(.6)	(.7)	(.7)
	(11) Fund size (USDmn)[1]	-1.2	-1.4	-1.4	-1.4	-1.4*	-1.2	-1.1
		(.9)	(.9)	(.9)	(.9)	(.8)	(.9)	(.8)
	(12) Avg. holding t. (Y)	-4.5***	-3.1**	-3.2**	-3.3**	-3.5***	-2.5	-2.4
		(1.6)	(1.4)	(1.3)	(1.3)	(1.3)	(2)	(2)
	(13) Reinvest. rate (%)	-1.1	-.9	-.9	-1	-1.3	-1.6	-1.5
		(.9)	(.9)	(.9)	(.9)	(.9)	(1.3)	(1.3)
	(14) Synd. share (%)	1.6	1.7*	1.6	1.5	1.7*	2	1.9
		(1)	(1)	(1)	(1)	(1)	(1.2)	(1.2)
	constants	2.7	1.9	3.3	1.8	5.3	3.1	3.3
		(5.3)	(4.8)	(4.8)	(4.4)	(4.9)	(4.6)	(4.4)
	Year dummy	YES	YES	YES	YES	YES	YES	YES
	Sec. spec. dummy	YES	YES	YES	YES	YES	YES	YES
	Fund type dummy	YES	YES	YES	YES	YES	YES	YES

Standard errors are in parentheses *** $p < .01$, ** $p < .05$, * $p < .1$ *Models highlighted in bold are standard models.*
1: This variable was logarithmised before calculating the pairwise correlation matrix.
2: Omitted due to linear dependence on o(1) and (2).

Table B-13: Overview of model results for robustness check

Discussion

Theoretical Contribution

In this study, I viewed entries in emerging technologies from an incumbent's portfolio viewpoint. I combined the perspectives of uncertainty reduction and entry timings (i.e., first and early mover advantages) and can thereby make three theoretical contributions.

First, I lift the discussion of first- and early-mover advantages to the level of technology entry portfolios. This is relevant because it is the perspective of primary relevance for incumbents facing uncertainties and making entry decisions frequently (Mitchell, 1989). Their perspective has been neglected in prior research around technology entry timings. I provide quantitative evidence that the advantage of *creator* entry strategies is also prevalent from the portfolio perspective and augment W. Kang & Montoya (2014) case study insights. I show that *creator* investor portfolio strategies generate superior returns, which answers the question of whether first-mover advantages hold when departing from a purely "survival rate"-based measurement (Agarwal & Bayus, 2004; M. B. Lieberman & Montgomery, 1998). By observing first mover advantages to being independent of the entered market, I show that the discussion about market individualities might be overstated and should receive lesser extension, particularly when confronted with a multitude of entries. On a portfolio level, facing great opportunities to gain from early investment outshines the high uncertainties associated with it.

Since entry timing is deeply intertwined with uncertainties, I viewed entry timing strategies as one (of many) uncertainty treatment strategies (i.e., diversification), broadening the scope of how to tackle uncertainties effectively. This leads to my other contributions.

Second, I show that uncertainty reduction treatments with a strong focus on information gathering (e.g., discovery and search) are prone to failure in the context of emerging technologies. This is relevant because strategizing and extensive information gathering is a behavior shown by incumbents (Furr & Eisenhardt, 2021). It creates the risk of a stark mismatch between incumbent routines acquired in low-uncertainty environments (traditional core business) and routines necessary to be successful in high-uncertainty ones (e.g., emerging technology entries), where "information is incomplete, unpredictable or unknowable" (Furr & Eisenhardt, 2021, p. 1921). From the perspective of emerging technologies, I object to recent publications (Shumilo et al., 2022) that incumbents need a thorough analysis of the external and internal environments leading to an actionable innovation strategy. My results confirm that following a predefined strategy can compromise performance, particularly when following an early timing strategy. Hence, other means of uncertainty treatment are required. My results suggest that experience plays a major role. Reducing inconsistencies during diversification strategies to reduce all "non-technology" uncertainties compensates for missing and unknowable information. This finding strengthens the arguments of Makarevich & Kim (2019) and Dimov & Martin de Holan (2010) that firms priorly obtained experience shape the way they see entry opportunities and reduce uncertainties, ultimately changing their search routines. Since sectorial consistency, in particular, successfully reduces uncertainty, I can confirm Van den Hoed's (2007) and Fatima's (2017) view that technologies are global phenomena and less dependent on regional effects. However, diversification as uncertainty treatment strategies cannot be considered in isolation; they depend on timing and interact with other treatments.

Third, I can show that uncertainty reduction treatments can have both positive and negative interaction mechanisms, while the direction of the interaction depends on the treatments and how they are conducted. This is relevant because it shows that doing "more" does not always lead to lower uncertainties and, thereby, better performance. After all, interactions are at play.

My results suggest, but do not prove (no analysis of sequential orders was conducted), splitting down the positive interactions further. This leads to three interaction mechanisms in the context of emerging technology entries: (1) *Supportive,* where more efforts in one treatment strategy lead to more success in another. (2) *Complementary*, where a positive feedback loop between treatment strategies benefits the effectiveness of both. (3) *Competing*, where more efforts in one treatment strategy obstruct the success of another. For example, in the *supportive* interaction, more diversification (market entries) could lead to more experimentation (contact with different business models and technologies) and more experience (knowledge and routines from diversification and experimentation). In turn, these effects can again lead to better *complementary* interactions. Diversification quality is enhanced if consistency in experimentation and experience building is maintained. On the other hand, information gathering (discovery and search) can lead to strategy inertia, which obstructs experimentation and diversification and thus reduces flexibility (competing). Not all information gathering is counterproductive for diversification; detailed and inflexible planning is ineffective only when information is limited, transient, and further analysis adds complexity (Arend, 2024e).

Practical Contribution

From a managerial perspective, I can deduce three recommendations. First, managers should assume that, on average, across their technology entries, a first-mover advantage exists. They should actively decide to pursue a portfolio entry timing strategy and be aware of the associated risks, especially of being strategy-inert when following early entry strategies.

Second, uncertainty cannot always be treated by gathering more information. The value of additional information has a diminishing marginal return. Some information cannot even be obtained because it is unknowable or will be outdated before it can be analyzed and translated into decision-making. In the context of emerging technologies, those uncertainty treatments perform better which focus on reducing non-technology uncertainties. Being consistent in the sectors where the new technologies are employed is one promising strategy. Most importantly, the success of uncertainty treatment strategies for emerging technology entries differs significantly from processes required in incumbents' traditional core business. This shows the value of a separate decision-making and uncertainty-reduction process. A potential for pursuing this is running a corporate venture capital entity.

Third, strategies for entering emerging technologies should be created as adaptable “guides”, accounting for changing circumstances, surprises, and new information to surface. Consequently, the amount of strategic planning and adaptation needs to be tailored to the amount of uncertainty involved in the entry decision (Packard & Clark, 2020).

Limitations and Future Research

My empirical setting holds several advantages. VC firms show traits in market entries that are also observable in classic incumbents but face market entry decisions more frequently. Public databases track them in great detail, isolating the observability of entry decisions' effect on performance from other operating effects. I follow other researchers (Lo et al., 2024; Makarevich & Kim, 2019) who use the venture capital industry as research objects to make generalizations. Nevertheless, I must point out that VCs face a lower barrier to engaging in new technologies by “simply” investing in one more portfolio company. For them, market entries are “daily business” and might thus be under greater scrutiny from top management personnel. Additionally, my dataset has the disadvantage of losing ca. 50% of observations due to an unfortunate combination of missing data points on the independent variables. I recommend using other databases (Retterath & Braun, 2020) to replicate my analysis.

My paper opens the possibility for further research. I encourage more researchers to view the dynamics of market entries from a portfolio perspective and not isolated industries or companies. This is especially beneficial for understanding the continuous entry performance of large corporations into new technologies. In this vein, private equity funds could be a comparable research subject for entries into mature markets or technologies that depart from my view, which is purely focused on emerging technologies. I suggest that fellow researchers examine whether the effects that are known to influence first-mover advantages on an industry level also hold on the portfolio level. Lastly, increasing research on uncertainty treatment interactions and their sequential order could give companies more apparent perspectives on how to treat uncertainties in decision-making.

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