The Path to Market-Maturity for Hydrogen in the Energy Industry

An Emergent Phenomenon in a Complex System

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Abstract

Title: The path to market-maturity for hydrogen in the energy industry - An emergent phenomenon in a complex system

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This study is concerned with the path of hydrogen towards market-maturity. The energy industry is being subject to radical changes triggered by the need to mitigate impacts of climate change. Hydrogen can play an important role as an energy storage technology to overcome periods of renewable energy production intermittencies and thus help decarbonising energy intensive industries. This research suggests that one must consider the energy industry as a complex system and study interagent behaviours when assessing the path to market-maturity. The analysis deals with five different levers which reflect on the concept of experience curves and that could potentially accelerate the cost reduction path. Due to interdependencies between energy producers and policymakers, this study proposes a form of coordination whereby policymakers set guard rails to which private agents adapt. Furthermore, the analysis tries to describe the development path for market ramp-up. It expects an exponential growth because of mutually reinforcing feedback loops that are created when political and private actions are coordinated. Finally, the findings imply that hydrogen can become an emergent phenomenon radically changing the energy industry and other adjacent industries.

Keywords*:* Hydrogen, Energy transition, Complex systems, Emergence, Energy producers, Policymakers, Market-maturity, Experience curves

Resumo

Título: O caminho para a maturação do hidrogénio no mercado da indústria energética - Um fenómeno emergente num sistema complexo

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Este estudo refere-se ao caminho do hidrogénio em direcção à maturidade do mercado. A indústria da energia está sujeita a mudanças radicais desencadeadas pela necessidade de mitigar os impactos das alterações climáticas. O hidrogénio pode desempenhar um papel importante como tecnologia de armazenamento de energia para superar períodos de produção intermitente de energia renovável e assim ajudar a descarbonizar as indústrias intensivas em energia. Este esforço de investigação sugere considerar a indústria energética como um sistema complexo e estudar comportamentos interagentes ao avaliar o caminho para a maturação do mercado. Portanto, a análise trata de cinco diferentes alavancas que reflectem sobre o conceito de curvas de experiência e que podem potencialmente acelerar o caminho da redução de custos. Devido às interdependências entre os produtores de energia e os decisores políticos, este estudo propõe uma forma de coordenação através da qual os decisores políticos estabelecem barreiras de protecção às quais os agentes privados se devem adaptar. Além disso, a análise tenta descrever a trajectória de desenvolvimento da rampa de acesso ao mercado. Espera um crescimento exponencial devido aos laços de feedback que se reforçam mutuamente e que são criados quando as acções políticas e privadas são coordenadas. Finalmente, as conclusões implicam que o hidrogénio pode tornar-se um fenómeno emergente e assim mudar radicalmente a indústria energética e outras indústrias adjacentes.

Palavras-chave*:* Hidrogénio, Transição energética, Sistemas complexos, Emergência, Produtores de energia, Decisores políticos, Mercado-maturidade, Curvas de experiência

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List of Abbreviations

PCA	Paris Climate Accords
CO_2	Carbon Dioxide
GHG	Greenhouse Gas
CAPEX	Capital Expenditures
EU	European Union
EMCI	Energy Mix Consumption Index
ETS	Emissions Trading System
PtG	Power-to-Gas
LCOH	Levelized Cost of Hydrogen

1. Introduction

> *"Accelerating, encouraging and enabling innovation is critical for an effective, long-term global response to climate change and promoting economic growth and sustainable development.[...]"* (Art. 10, Para. 5, Paris Climate Accords, 2015)

In 2015, the world united to address the greatest challenge for humanity, climate change, by adopting the Paris Climate Accords (PCA). Decarbonization of the global economy through innovative solutions was declared an imperative by the United Nations (United Nations, 2015). Energy production is one of the main contributors to carbon dioxide (CO_2) emissions (McKinsey, 2022). With accelerating transformation towards sustainable energy production, the question of energy storage becomes increasingly important. Renewable energy such as solar and wind depend on weather conditions, which is why phases of intermittency must be bridged to ensure constancy of supply (Anderson & Leach, 2004). To this end, hydrogen has been proposed as a potential energy storage technology. But compared to other alternative energy sources, it is not yet market mature due to production capacity and non-competitive pricing (Goldman Sachs, 2022). Ramping-up hydrogen implicates a network of technical factors, market conditions, and stakeholders.

Bass and Grøgaard (2021) have outlined how a variety of stakeholders and industry drivers influencing energy transition. Hydrogen development also requires complex mechanisms that affect the overall energy transition phenomenon (Walker et al., 2016). Of course, introducing any new technology implicates different agents and leads to repercussions for an entire system (Bale, Varga & Foxon, 2014). Thus, researchers have proposed that managerial, regulatory and other factors must be considered in a systemic light when performing analyses to understand the changing energy environment (Bass & Grøgaard, 2021). The interplay of agents in the system (such as public and private actors), as well as the impact of using hydrogen as a key energy source for the energy industry, need unpacking. With hydrogen being relatively unexplored, this paper seeks to contribute to the discussion of hydrogen as an energy alternative. The thesis examines the following research questions:

1a) What steps need to be taken for hydrogen to become a market-mature substitute for fossil-fuels?

1b) How can energy producers and policymakers collaborate to create an environment where hydrogen is able to develop?

2) Does hydrogen have the potential to become an emergent phenomenon in the complex system of the energy industry or will it only have an incremental impact?

The following illustration shows the intersection of different research fields that determine the research area to which the research questions are intended to contribute.

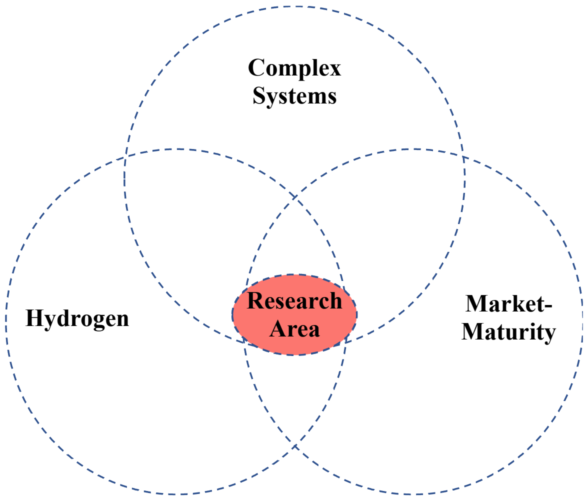

Figure 1. *Illustration of Research Area*

2. Literature Review

This paper focuses on hydrogen as a technological driver in the energy industry and also strives to contribute to research on economic complexity. The first subchapter provides general insights on the energy industry followed by an overview of complex systems theory in light of the energy sector. Subsequently, hydrogen as an innovative technology and its potential emergent characteristics are discussed.

2.1 Review of Public and Private Actors’ Behavior in the Energy Industry

The energy sector is facing major centrifugal forces triggered by decarbonization and the transition away from fossil fuels towards sustainability. The industry is comprised of various stakeholders with different motives inside the so-called energy trilemma: 1. how to ensure affordable energy prices, 2. how to reduce greenhouse gas (GHG) emissions, and 3. how to provide secure energy supplies (Ridha, Nolting & Praktiknjo, 2020; Bale, Varga & Foxon, 2014). Bale et al. (2014) highlight stakeholders, including producers, generators, suppliers, public institutions, and end consumers, who prioritize different goals during the industry’s current transformation. Factors influencing behavior include the different technologies being used to convert energy into electricity or fuel (Ridha et al., 2020). Various industry forces also shape the transition towards net-zero energy. These include policy regulation and public subsidies, research and development activities by firms, and also changing consumer and investor preferences towards renewable energy (McKinsey, 2022; Costa-Campi, Duch-Brown & García-Quevedo, 2014). Other relevant factors include accessibility and transferability of commodities, infrastructure including high capital expenditures (CAPEX) requirements, as well as price-building mechanisms (McKinsey, 2022; Ridha et al., 2020).

This paper also sheds light on the relationship between public institutions and energy producers focusing on the European Union (EU). The latter is comprised of heterogenous energy markets with regard to the energy mix and infrastructure.

2.1.1 Introduction of Measures of Regulatory Policy Intervention

Energy consumption is strongly correlated to general economic drivers. With energy commodities being price inelastic, policy makers often step in to ensure affordable energy and economic growth (Belke, Dobnik & Dreger, 2011). EU economies are dependent upon energy resources and governments have established state-owned energy companies to produce and distribute energy and to steer domestic energy policy (Nicolli & Vona, 2019). In recent decades, however, energy markets in the EU have undergone a process of market liberalisation (Nicolli & Vona, 2016). This has led to privatisation of public utilities and a decoupling of transmission systems operators from energy producers while promoting competitive market forces and creating independent players along the value chain (Nicolli & Vona, 2019). However, energy markets remain rather country-specific with few incumbents and high barriers to entry because of the capital intensity of building production plants (Nicolli & Vona, 2019; Nicolli & Vona, 2016).

Liberalization sought to decrease market concentration and establish an internal energy market in the EU. This contrasts with arguments for strong policy intervention and regulation to ensure affordable energy (Song, Wang & Zhang, 2020). Beyond seeking supply and cost stability, energy policies of industrialised countries have further incorporated a third imperative – reducing GHG emissions under multilateral agreements to battle climate change (Howard-Grenville, Buckle, Hoskins & George, 2014). Political influence and policy intervention thus have a strong impact on the structural characteristics of the energy sector, illustrated in the

Energy Mix Consumption Index (EMCI) of the German energy market shown in Appendix 1. The share of fossil fuels in the EMCI has become smaller and renewable energies have experienced a significant uptick. This has been driven by changing societal and political opinions and also been enabled by technological break-through innovations (Bass & Grøgaard, 2021). To accelerate transition towards renewable energy, the EU introduced a comprehensive plan that stipulates reduction of CO_2 emissions[1] by 55% to 2030, and eventual climate neutrality by 2050 (European Commission, 2021). Accounting for more than 70%[2] of the total CO_2 emissions in the EU, the energy sector is a decisive factor when it comes to energy transformation (Eurostat, 2022). Efforts to dramatically reduce emissions and accelerate expansion of renewable power plants have been addressed through different policy measures by the EU. *Inter alia*, this includes certain political interventions, enhanced research and development funding, additional subsidies and deploying new and more sustainable technologies (Scarlat, Prussi & Padella, 2022).

2.1.2 Price-Building and Cost Reduction Mechanisms in the Energy Market

As outlined in the introduction, hydrogen is currently not competitive, which is why the following subchapter sheds light on price building mechanisms of energy commodities. The second subchapter then deals with cost reductions.

2.1.2.1 Price building mechanisms of energy commodities

Energy commodities are heterogenous with access depending on spatial and temporal constraints. Renewable energy, for instance, varies according to weather conditions and transportation from sites of production to consumption rely on existing infrastructure (Hirth, Ueckerdt & Edenhofer, 2014). As mentioned in Chapter 2.2.1, the EU has introduced measures to abate CO_2 emissions. To overcome lack of infrastructure for renewables, policy interventions have been directed at making CO_2 emissions more expensive, thus incentivising the switch from fossil-fuels. The impact of emissions trading systems (ETS) has been discussed by many scholars (Scarlat et al., 2022; Lin & Jia, 2017; Abrell, Faye & Zachmann, 2011). It integrates a cap-and-trade limit for GHG allowances to mitigate negative externalities through price surcharges (Scarlat et al., 2022). In general, short-term commodity prices are negotiated in the

[1] CO_2 equivalents (CO_2e) are referred to as CO_2 emissions
[2] Own calculation by dividing the energy emissions with the total emissions

spot markets and determined through the merit-order effect shown in the illustration below (Sensfuß, Ragwitz & Genoese, 2008):

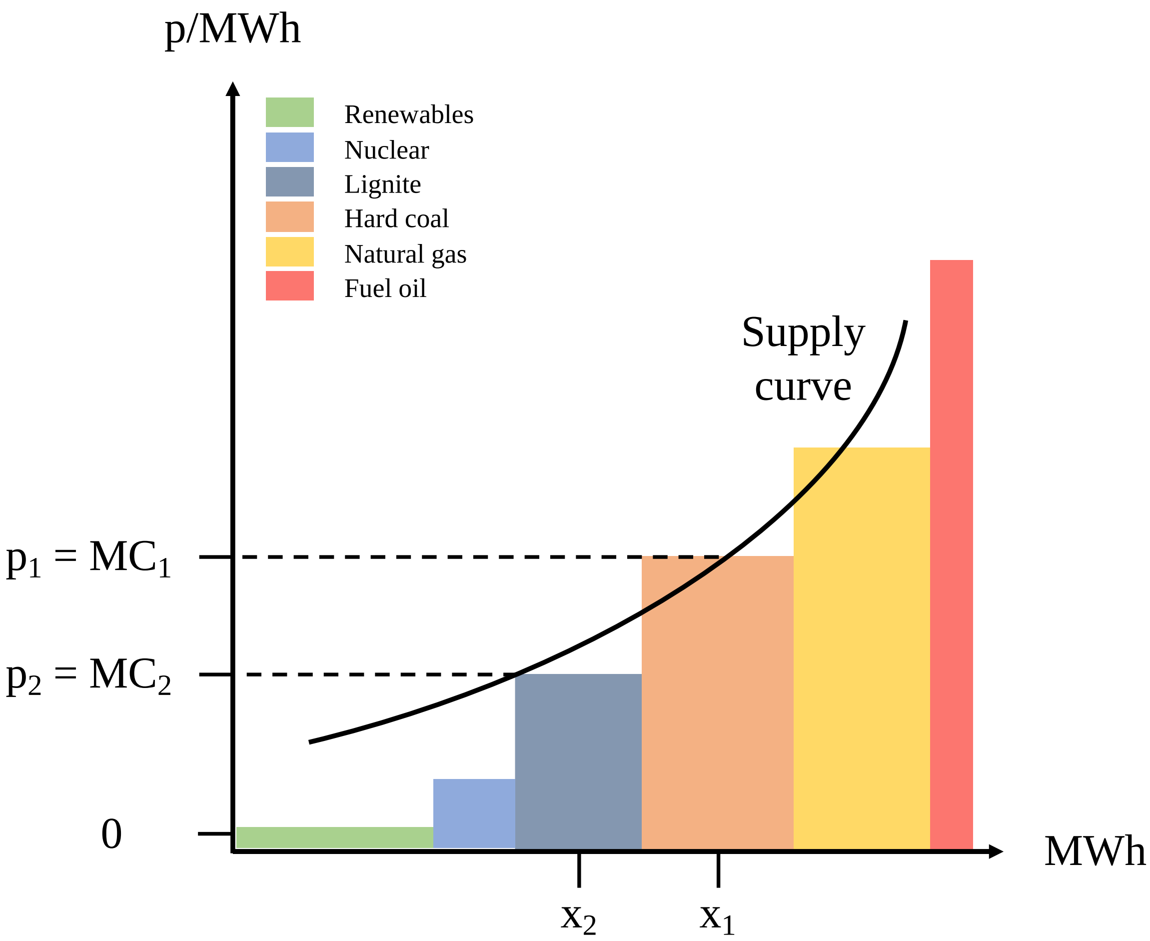

Figure 2. *Merit-Order Effect; adapted from Cludius et al., 2014; Sensfuß et al., 2008*

As shown in Figure 2, price of a unit MWh is determined by the marginal power plant producing each energy type needed to satisfy demand. Since marginal costs differ between energy sources, the price building mechanism for a merit-order effect depends on the quantity of renewable energy produced in the global market dominated by fossil-fuels. Increasing demand during peak load times means that energy shifts further right on the supply curve and energy prices increase. At times when renewables do not supply enough energy to satisfy even the base load, additional energy is fed-in from costlier fossil-fuel power plants that have higher marginal costs, resulting in higher energy prices. In the example provided in Figure 2, this means that if the quantity supplied increases from x_1 to x_2, the energy source that determines price, shifts from lignite to hard coal which leads to a price increase from p_2 to p_1.

2.1.2.2 Firm-learning as a mechanism for cost reductions

Research suggests that higher GHG prices promote investment in technological innovation to reduce carbon emissions. But in spite of decreasing attractiveness of commodities with high CO_2 footprints, investments are being channeled towards immature technologies rather than innovation (Gasbarro, Rizzi & Frey, 2013). Reluctance to accelerate investment in low-carbon technologies is exacerbated by high initial costs and uncertainty about returns (Gasbarro et al., 2013; McGrath, 1997; Reece, 1986).

Various factors influence slow adoption of new technologies. As is shown in Figure 2, prices are determined by the marginal costs of respective energy carriers. If the price of one commodity becomes higher than another, it will immediately be substituted. The generally accepted concept of experience curves developed by the Boston Consulting Group suggests that costs will decline over time due to patterns of improving input-output factor ratios (Henderson, 1984). While learning curves mainly refer to organizational learning, experience curves pertain to the development in aggregate of an entire industry in the process of embracing new technologies and evolving cost reductions (Nemet, 2006). Research indicates that this phenomenon of declining costs is caused by four factors: (1) initiating investment to obtain *ex post* benefits; (2) eliminating waste to scale productivity; (3) substituting input factors to improve the input-output ratio; and (4) acquiring additional knowledge to increase productivity (Henderson, 1984). Traditionally, the idea of experience curves has been used to assess cost structures and derive strategic assumptions for managers. Henderson (1984), however, highlights that experience curves can be used not just for defining firms' long-term strategies but rather as a holistic economic framework. He proffers experience curves as a tool to study effect mechanisms in whole industries. This idea has been picked up by several scholars studying energy technology such as for photovoltaics (Bhandari & Stadler, 2009; Neij, 1997); wind power (Neij, 1999); or fossil-fuels such as coal and oil (Yeh & Rubin, 2012).

2.2 Energy Industry as a Complex System

> "*Science has explored the microcosmos and the macrocosmos; we have a good sense of the lay of the land. The great unexplored frontier is complexity.*" (Pagels, p.12, 1989)

This famous quote by Heinz Pagels (1989) points to a paradox of how humans have been able to study problems that are highly complex and yet researching the underlying mechanisms of cause and effect in the context of complexity makes us resort to over-simplifications, reductive generalizations, and other heuristics. The groundwork of complex system studies was laid by the Santa Fe Institute where researchers sought to understand ever-changing evolutionary connections in economic systems and develop a research approach that would more accurately reflect the realities of economic conditions (Anderson, 1999).

Complex systems can be defined as "[..] co-evolving multilayer networks" **(**Thurner, Hanel & Klimek, p.22, 2018). A complex system is thereby shaped through the aggregate behavior of different agents that act individually within the system, creating a perpetual mechanism of adjusting the behavior to altering environmental conditions (Holland & Miller, 1991). The interactions between different agents and the underlying environmental conditions allow for a broad variation of structures within the system (Thurner et al., 2018). The state of a system is thereby defined by the concrete forms of interactions between these different influencing factors, a phenomenon referred to as 'emergence' in complex systems theory (Anderson, 1999). Goldstein (1999) applies the term "gestalt" which originates from Johann Wolfgang von Goethe to describe the respective form arising out of ordered chaos from all possible configurations that are enabled as emergent phenomena. The following section seeks to derive propositions from the criteria that determine emergence in complex systems:

(1) *Numerosity* refers to the fact that when there are a large number of agents in a system, with multiple interactions and hierarchies between those elements, this leads to degrees of complexity (Ladyman, Lambert & Wiesner, 2013). *Interdependencies* in a dynamic system shape the identity and function among different agents (Goerner, 1994), reinforcing complexity as structures evolve simultaneously and actions become mutually constituting, causing agents to align their behaviors (Bergmann Lichtenstein, 2000). As outlined in Chapter 2.1, the different stakeholders, technologies and multiple industry and market specifics create high levels of complexity associated with the transition towards carbon neutrality. The number of different agents in the system create a network of interdependent causal mechanisms interacting dynamically, which demands a holistic approach when looking at energy transition (Kern & Smith, 2008).

Proposition 1: When analyzing agents' behavior in the energy industry, the effect mechanisms are complex and multilayered, which is why research methods need to focus on interactions among agents and the hierarchies inherent in the system.

(2) *Non-linearity* describes the notion that a system is not necessarily the sum of its singular parts but rather a result of reinforcing mechanisms (Vance, Groves, Paik & Kindler, 2007; Waldrop, 1992) Early research by Lewes (1875) showed that non-linearity within systems can be explained through surrounding factors that create amplifying effects of different components. Thus, non-linear results can be explained by synergy effects from *feedback loops* between connected agents in a complex system (Ladyman et al., 2013). In the energy sector a different number of feedback loops have the potential to rapidly transform global energy systems (State Street Global Advisors, 2021). These various feedback loops have significant impacts over time with multiple positively and negatively oscillating cause-and-effect relationships (Sterman, 1994). Therefore, change in one or more parts can yield highly nonmonotonic reactions and unexpected behavior of the overall system (Ethiraj & Levinthal, 2004). Unpredictability is how complex systems evolve over time. An example is the so-called "butterfly effect" (Lorenz, 1993) where small changes have large effects. This suggests that sequences of intertwining feedback loops and reinforcing effect mechanisms of even small deviations can create completely distinctive significant outcomes (Gleick, 1987). This is corroborated by observing how renewables have developed and influenced global energy production. Although being costly, the shift to renewable energy production has radically changed the industry (Gielen et al., 2019). Costs have become significantly lower suggesting that the effect of feedback loops creates an amplification through interagent collaboration (Weiss et al., 2010).

Proposition 2: The effect of learning through feedback loops must be elaborated to understand interactions between agents in complex systems.

(3) *Connectivity* describes different agents collaborating across organizations, institutions, or geographical spaces of a comprehensive network (Cano-Kollmann et al., 2016). Such networks facilitate and also constrain behavior, forcing adaptations to the surroundings (Anderson, Håkansson & Johanson, 1994). Agents self-organize as they evolve over time. Consequently, the network is a driver of change, and is itself reflexively shaped by the behavior of agents over time (Chandra & Wilkinson, 2017). In the past, mechanistic worldviews were more common along with analytical reductionism. Here, certain elements of a system are singled out and studied individually with causal conclusions derived from them (Agazzi, 1978; Jessor, 1958). However, in an increasingly complicated world, more holistic and nuanced approaches are

necessary for studying complex systems. Interactions between elements within a system cause interdependencies and elicit reciprocal behaviors (Anderson, 1999). Yet, there is still a tendency to ignore the significant interplay between agents in complex systems (Ritter, Wilkinson & Johnston, 2004). The same applies for the energy industry where research often focuses on the connection of public and private stakeholders through regulation, insinuating a preponderance of policy maker determinants (Fischer et al., 2020). However, Witt (1997) argues that economic systems must be seen as dissipative systems of agents constantly interacting with the system, who also practice self-organisation. In contrast to natural dissipative systems, they are influenced by human actions and intelligence and the desire to advance ideas through knowledge enhancement (ibid.). In the energy sector this desire to develop innovation that can help shape the transition to renewables is mainly influenced by political and industrial networks (Mattes, Huber & Koehrsen, 2015). In past energy transitions governments interfered less and producers and consumers had intrinsic motivations to carry out transformation. However, the current transition is mainly driven by an overriding societal motivation to lower CO_2 emissions so greater governmental engagement is needed to accelerate change (Fouquet & Pearson, 2012). This line of argument aligns with Leach (1992, p.121) who describes the motivation of political stakeholders as "[…] to interfere with the 'natural' transition process". Due to the interplay of energy producers with surrounding governance structures and vice versa, self-organisation can be regarded as a constant process accompanying energy transition (Hasanov & Zuidema, 2018). The existence of connectivity can, therefore, be assumed however it is limited in that self-organization is also aligned with regulatory requirements (Aghion et al., 2016; Witt, 1997).

Proposition 3: A research approach is suggested that seeks to understand the self-organizing effect mechanisms of agent behavior with a specific focus on public players and energy producers.

(4) *Adaptation* refers to how changes in environmental conditions affect agents and their surroundings. The symbiotic relationship between agent behavior and a dynamic environment defines the evolution of the group as a whole (Arrow, McGrath & Berdahl, 2000). Symbiosis in the system as a whole is the determinant factor that creates a complex adaptive system (Anderson, 1999). As there is no centralized coordination mechanism, a complex adaptive system relies on agent-driven levels of self-organization leading to systemic development on the macro-scale (Chandra & Wilkinson, 2017). Emergent phenomena in complex systems can

thus be described as patterns where the output of the system in time *t* directly affects the input in time *t+1* (Carmichael & Hadžikadić, 2019, Holland & Miller, 1998). The constant process of feedback interactions between agents and the system results in continuing states of non-equilibria (Foster, 2005). Complex systems theory is essentially the study of dynamic interconnectedness within a system and not the study of discrete system elements (Potts, 2000). Yet, effects of different connections do not influence a complex system in equal ways. Instead, influential agents have critical systemic influence (Lambiotte, Rosvall & Scholtes, 2019; Schilling & Fang, 2014). Despite energy market liberalisation and the associated difficulty to implement policy change, it is not energy producers only who play a key role in the transition but also political stakeholders (Pollitt, 2012). The existence of highly interlinked agents with stronger inter-agent concentrations and shorter paths of interaction significantly affects the aggregate behavior of the system as a whole (Uzzi, Amaral & Reed-Tschochas, 2007; Goyal, van der Leij & Moraga-González, 2006).

However, for the energy sector this is not trivial as past adaptation processes have created a path-dependency leading to economic lock-in effects exploiting fossil energy sources (Barazza & Strachan, 2021). This path-dependency is enhanced through the existence of sunk costs and an associated reluctance to invest in green technologies (ibid.; Barham, Chavas & Coomes, 1998). The strong orientation of the whole system towards fossil fuels characterizes the adaptive nature of the energy sector (Barazza & Strachan, 2021). It was suggested above that agents in the energy sector interactively self-organize within the system, and the need for enhanced policy engagement was highlighted (Fouquet & Pearson, 2012). According to Aghion et al. (2016) existing adapted structures associated with fossil fuel energy production must essentially be broken up by political measures. In contrast to natural complex systems, economic ones are not only dependent on natural self-organisation but also react to regulatory specifications indicating the need for "*[...] 'viable' coordination [...]*" by regulatory stakeholders (Witt, 1997, p.506).

Proposition 4: To fully comprehend effect mechanisms in the energy industry, observing symbiotic relationships between agents rather than behavior of single agents in a vacuum must occur, taking into consideration the stronger influence of regulatory agents than other stakeholders in shaping the system.

Clearly, the energy industry can be seen as a complex system. This corresponds with existing literature denoting the industry as such and implicating complexity theory as an appropriate tool for analyzing it (Ridha, et al. 2014). Additionally, the case has been made that economic systems, such as the energy industry, differ from natural complexity by their responsiveness to being steered by centralized regulation to achieve a critical state when inflection points occur that change the dynamics of the system (Aghion et al., 2016).

Nicholas Nasim Taleb's (2013, 2018) distinction between Mediocristan and Extremistan is a metaphor that also distinguishes Gaussian mean variant phenomena from events located in complex systems, where outsized systemic consequences occur. Change in the Extremistan system is fat tailed, unpredictable, and therefore not amenable to having definitive probabilities assigned to it (Taleb, 2018).

2.3 Introduction of Hydrogen as Alternative Energy Source

Innovative and carbon-neutral energy storage technologies have raised researchers' attention (Muradov & Veziroglu, 2008). Since weather makes renewables unreliable for ensuring baseload demand, excess capacity on windy or sunny days needs to be stored to backstop days with weak production conditions. Therefore, technologies are needed including more advanced batteries, synthetic fuels, or natural and carbon-free gases such as hydrogen (Walker, Mukherjee, Fowler & Elkamel, 2016). Hydrogen does not provide a competitive alternative for existing energy carriers since it has not yet reached market maturity (Kakoulaki et al., 2021). This paper examines how hydrogen may become a competitive substitute for carbon-heavy energy sources. Affordability of energy is crucial given the high price elasticity associated with different energy sources. Cost increases lead to market reactions caused by the merit order effect, which is why hydrogen costs must be competitive. As hydrogen is a secondary energy source, production costs of the different hydrogen colors are linked to spot prices of primary energy sources, CAPEX, and other variable costs (Parra, Valverde, Pino & Patel, 2019). A comparative illustration of costs of grey and green hydrogen is provided in Appendix 2. The illustration shows higher price levels for green hydrogen and that price is highly volatile.

Hydrogen has different possible applications, for instance, as a basic material in the chemical industry. It is a fuel but can also be used as an energy carrier. Being an element available in abundance and given its circular characteristics, hydrogen has become increasingly important as a supplement to primary energy sources (Walker et al., 2016). Although there are multiple use cases for hydrogen, this paper focusses on hydrogen as a sustainable addition during energy transition. The degree of sustainability of hydrogen, however, depends on the primary energy sources used for the hydrogen production process (ibid.). Appendix 3 based on research by Ajanovic, Sayer & Haas (2022) provides an overview of different hydrogen production processes. Green hydrogen is produced through electrolysis that splits water into hydrogen and oxygen. The reverse process of combining hydrogen and oxygen creates an enormous amount of energy in the chemical oxyhydrogen gas reaction (Ajanovic et al., 2022). This general process of energy storage and reconversion is subsumed under the term Power-to-X. Using this technology to store electricity by altering physical states to produce hydrogen is termed Power-to-Gas (PtG) and can be integrated into the energy system. It is therefore important to supplement renewable energies to balance fluctuating supply that occurs in times of low wind or sun. On days with excess capacity, energy can be stored as a compressed gas and brought back later into the energy cycle when supply cannot satisfy demand (Walker et al., 2016). Hence, PtG can be seen as an important pillar of renewable energy transition as it helps replace fossil fuels by storing renewable energy generated, thus mitigating CO_2 emissions (ibid.).

2.4 Emergence of Hydrogen in the Energy Industry

Bale et al. (2014) suggest that the energy industry is a complex system that can be changed significantly through new technologies. Thus, to elaborate on the first research question, the following chapter analyses how hydrogen might become an emergent phenomenon for the energy industry. To conform to the definition of emergence in a complex system, hydrogen must fulfil the four criteria presented in Chapter 2.2:

(1) The first criterion that characterizes emergence, numerosity, reflects the numerous factors that influence the system. Different stakeholders within the energy sector as well as in adjacent industries and in regulatory bodies influence successful deployment of hydrogen as a key energy source (Schlund, Schulte & Sprenger, 2021). The broad application of hydrogen offers potential not only in the energy sector but also in other energy-intensive industries such as transportation, chemical and raw materials. The following application illustrates the value chain of hydrogen and the stakeholders affecting deployment.

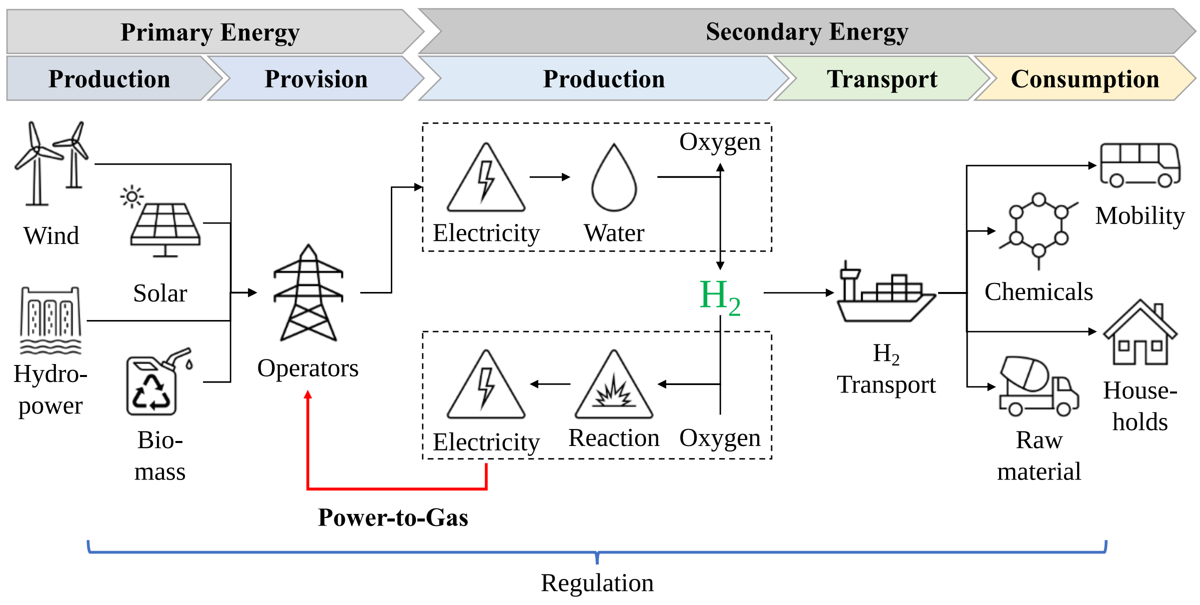

Figure 3*. Hydrogen Value Chain; adapted from Ajanovic et al., 2022; Fan et al., 2021*

Figure 3 displays stakeholders upstream and downstream in the value chain. Key upstream stakeholders for hydrogen are producers and operators of primary green energy. After the primary hydrogen is produced, storage and transport as well as delivery to end consumers completes the value chain. Due to the strong regulatory requirements of the energy industry, public authorities remain a crucial stakeholder along the entire hydrogen value chain (Goldman Sachs, 2022). Due to heterogenous local, regional and cross-border energy markets, the number of stakeholders varies across different markets which increases multipolarity even further (Hirth et al., 2014). Therefore, the deployment of hydrogen arguably shows a high extent of stakeholder numerosity.

(2) The second criterion of emergence is non-linearity which describes a system being more than simply the sum of its parts. Instead, it exhibits nonmonotonic characteristics due to mutually reinforcing dependencies. These non-linear and amplifying results can be explained by synergies arising from coordination activities of different agents in the system. In the energy sector, interactions between public actors and energy producers are important for bringing about energy transition (Tzankova, 2020). Research demonstrates that government engagement can create strong synergetic effects if policy measures are coordinated and the private sector is prepared to absorb government support (Wu & Hu, 2020). Similar to prior technological revolutions, energy transition follows the typical arc of decreasing costs resulting from feedback loops (State Street Global Advisors, 2021). Such learning effects are caused by

mutually reinforcing experiences and are specifically observable in systems that show nonlinear trajectories (Farmer et al., 2019). This phenomenon has also been examined by scholars of hydrogen (Nicodemus, 2018; Schoots et al., 2008). Nicodemus (2018) mentions significant potential cost reductions through learning effects while Schoots et al. (2008) compared different hydrogen production processes and found that declining costs can only be expected for green hydrogen. This can be explained through the concept of experience curves which underline the potential synergies associated with hydrogen development. Therefore, the existence of non-linearity can be assumed.

(3) Connectivity is the third criterion indicating an emergent phenomenon where a system is composed of different agents who are interdependent but nevertheless influenced by the actions of other agents (Anderson et al., 1994). As presented in Figure 3, the hydrogen value chain entails a large number of mutually dependent stakeholders. These interdependencies become even stronger considering how liberalised energy markets have led to interactions between agents from diverse locales (Lienert & Lochner, 2012). For hydrogen to be deployed, the connection between energy producers and regulators has been highlighted by researchers (Kovač, Paranos & Marciuš, 2021). Furthermore, as reflected in Figure 2, different energy sources are also an important factor when examining interdependencies. Since price fluctuations of one energy source can lead to beneficial market conditions for others, there is also resource interconnectedness (Lienert & Lochner, 2012). Thus, development of hydrogen as an energy source is embedded in a network of distinct stakeholders, heterogenous markets and disparate other energy sources (Fan et al., 2021). For that reason, it can be concluded that the development of hydrogen is influenced by connectivity to a network of comprehensive effect mechanisms.

(4) The fourth criterion of an emergent phenomenon in a complex system is adaptation of the whole system. The system and agents in it are perceived to act symbiotically since individual behavior of agents shapes the system as a whole (Arrow et al., 2000). Although there is no centralised mechanism of top-down coordination, the system evolves through the aggregate self-organisation of all the agents (Chandra & Wilkinson, 2017). This can be observed in the energy industry which consists of heterogenous elements interacting at the macrolevel and adapting behavior on a microlevel thus influencing system change (Deissenroth et al., 2017). In the sector, firms are forced to align their business models to shifting macro trends (Bohnsack, Ciulli & Kolk, 2021).

As a technology for energy storage, hydrogen is becoming increasingly important in the transition away from fossil fuels (World Economic Forum, 2022). After slow deployment of hydrogen initially, it is assumed that hydrogen electrolysers will be installed at increasingly large scale from 2030 onwards. Therefore, hydrogen will be important for decarbonizing energy-intensive industries (Kovač et al., 2021). Whereas agents in the system are forced to adjust behavior to conform to changing environmental norms associated with energy transition, the system itself is also evolving at the macro level through micro level decisions. Consequently, the criterion of adaptation can be assumed to exist for hydrogen technology.

In summary, the literature suggests that hydrogen may be taken to be an emergent phenomenon in the energy industry.

3 Methodology

This chapter seeks to outline the general research approach used in this paper. An overview of the research structure is depicted in the following diagram:

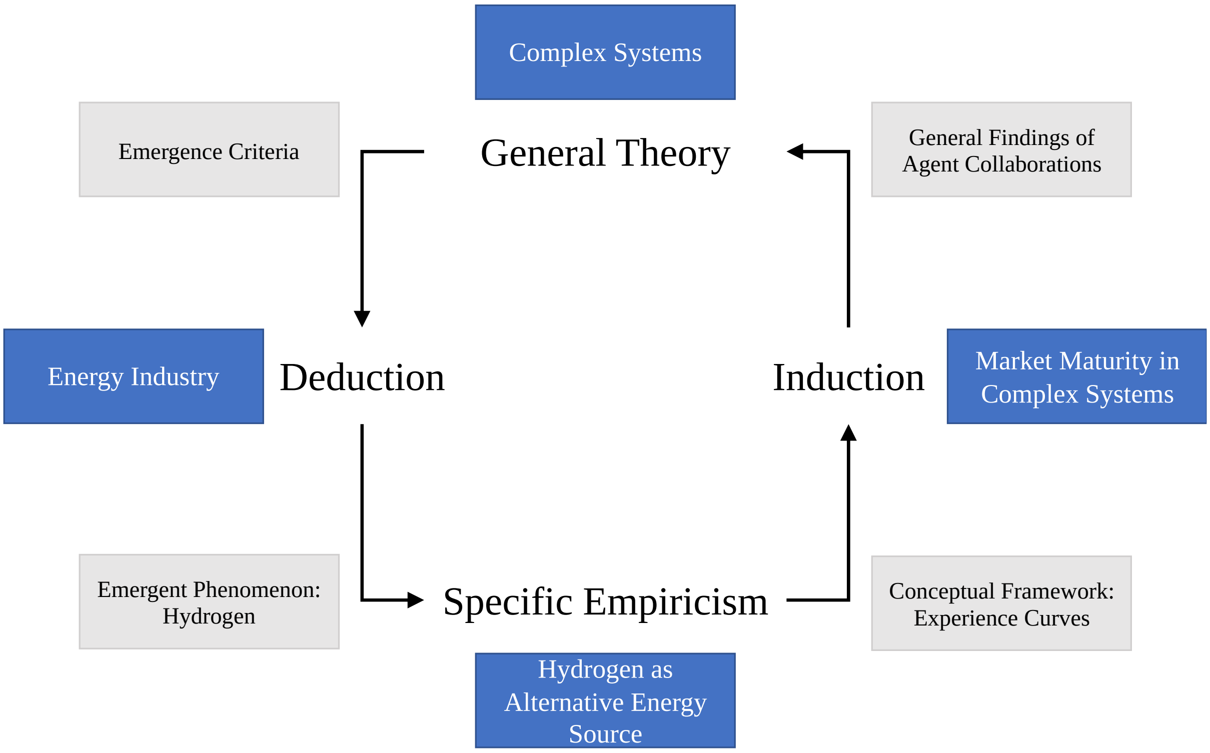

Figure 4. *Research Approach*

Figure 4 visualizes the research approach of this paper that seeks to combine complexity research with the hydrogen case on its path to becoming a market-mature alternative energy source. By applying complex systems theory, it was deduced that the energy industry can be considered a complex system and hydrogen considered to be an emergent phenomenon within that complex system. In the analysis section, groundwork shall be laid to understand what measures need to be taken before hydrogen can become market mature. Lastly, those findings shall be used to create general assumptions that contribute to the overarching study of complex systems.

3.1 Research Design

The research design for this thesis combines qualitative research design with a quantitative analysis part. Qualitative research can be used for insights that are transposed from practical experience (Mayring, 2014). Furthermore, it can be applied to understand the how and why of complex processes and when a lack of research exists (Benbasat, Goldstein & Mead, 1987). As outlined in previous chapters, this paper focusses on understanding a new technology in a complex system. Relying on suggestions by Benbasat et al. (1987), a qualitative research design was chosen. In the following subchapter 3.1.1, the structured content analysis research method which was developed by Mayring (2014) shall be introduced. The quantitative insights based on public and private data shall be explained in more detail in the subsequent subchapter 3.1.2.

To provide findings that contribute to the overall study of complex systems, four propositions were introduced in Chapter 2.2 outlining a research approach -- the need to analyse stakeholder interactions within the hierarchies of the system; the effect of learning through feedback using the concept of experience curves; the aspects of connectivity and self-organisation; lastly, the idea of adaptation referring to evolution of the industry through the development of hydrogen. Through the analysis in Chapter 4 and the discussion part in Chapter 5.2, the question of the repercussions of hydrogen as energy source on the energy industry shall be discussed.

3.1.1 Deductive Content Analysis of Expert Interviews

To elaborate the research questions, ten expert interviews were conducted. The interviews followed a semi-structured approach aligned with the Mayring method for content analysis (Mayring, 2014). The questionnaire and a detailed list of the expert interviews are shown in

Appendix 4. The method, displayed in Figure 5, was chosen to guide the author's qualitative research and generate balanced insights. After the first step of contextualizing questions with regard to insights from the literature, categories for lines of questioning were developed. These were derived in an induction-deduction combination. Conclusions from existing theoretical as well as practical literature were isolated and followed by a pilot interview to test the categories (Mayring & Fenzl, 2019). The preliminary coding framework and coding rules were developed in light of research questions *1a* and *1b*, to connect current shortcomings of hydrogen and assess whether energy producers or public agents are responsible for solving them. After iteration of the category structure and coding rules to fit the insights acquired, further interviews were conducted. Lastly, the category insights were evaluated to draw conclusions.

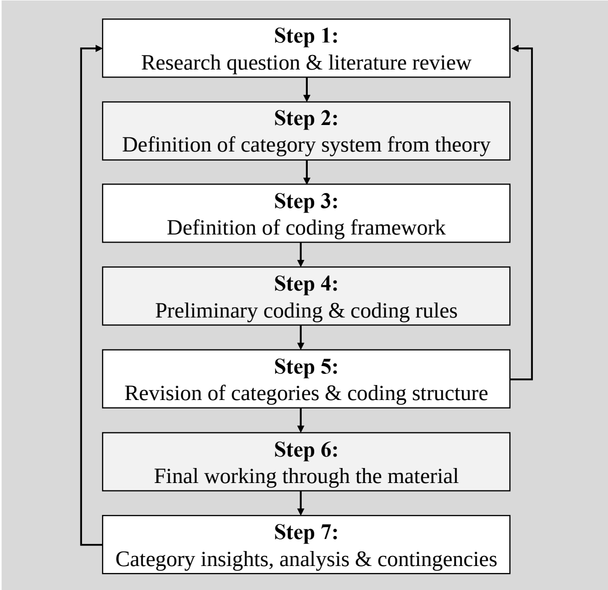

***Figure 5**. Content Analysis Process; adapted from Mayring (2014)*

3.1.2 Sample of Energy Data

For the quantitative analysis, publicly accessible data from the German think tank *Agora Energiewende* was used. This entity supplies live data of energy production for different energy sources in the German energy market including daily energy prices and daily CO_2 emissions. The LCOH data was provided by the German-Dutch firm *E-Bridge Consulting GmbH* that gathers daily hydrogen cost data in their hydrogen index 'Hydex'. For comparative analysis of different variables, daily data points were scraped for the period 01.04.2021 to 01.04.2022. The German market was chosen due to publicly accessible data and because it is currently the country with the biggest investment pledge towards hydrogen (Goldman Sachs, 2022).

For the computations, simple regression analyses were conducted in R to generate insights about the relation between energy production capacities and energy prices. As stated in Chapter 2.3, hydrogen costs are currently not competitive vis-à-vis other energy carriers. To understand hydrogen cost drivers, the influence of energy production capacities on hydrogen were examined. Therefore, LCOH data was compared with the renewable energy production levels.

3.2 Cost Reductions through Experience Curves in Complex Systems

This subchapter describes the theoretical framework of experience curves presented in Chapter 2.1.2.2. This concept is applied for two reasons. Demand for an energy commodity reacts inversely to price increases of a substitute commodity. For hydrogen to become an alternative to fossil fuels, it needs to trade at price levels that are similar to its competing energy sources (Sweeney, 1984). Exploiting experience curve strategies is particularly meaningful in an environment where demand is sensitive to price changes and the product is rather early in its lifecycle (Ghemwat, 1985). For these reasons, the concept of experience curves would seem applicable for analysing declining costs for hydrogen. Cost reduction is the result of multiple interactions in a complex system (Henderson, 1984). Therefore, the concept of experience curves helps break down complexity to explain cost reductions and can thus clarify the path to market-maturity of hydrogen (Schoots et al., 2008, Henderson 1984).

Five categories were developed in the deductive content analysis, reflecting the four factors that determine experience curves and associated cost reductions. The translation logic of experience curves that factors into categories of analysis for hydrogen is illustrated in the following table:

Experience Curve Factor	Analysis Category	Chapter
(1) Initiation of investments	1. Capital allocation	4.2.1
(2) Elimination of waste	2. Price building	4.1.2
(3) Substitution of input factors	3. Infrastructure	4.1.1
(4) Acquisition of additional knowledge	4. Research & know-how 5. Corporate partnerships	4.2.2 4.2.3

Table 1. *Experience Curve Factors*

Initiation of investments refers to the need to fund CAPEX to improve output. The analysis of current capital allocation is picked up in the capital allocation category. Secondly, elimination of waste delineates any effort that is not used to add value to the product. The term waste is conceived broadly as it entails wasted time or energy (Henderson, 1984). To date there is no comprehensive market for hydrogen which makes it impossible to trade on a large scale (Schlund et al., 2021). A well-functioning market, however, is supposed to distribute scarce goods efficiently, reduce resource waste and create transparency over supply, demand, and prices (Williamson, 1979). A market further lowers transaction costs by increasing the frequency of interactions and reducing uncertainty of market participants (Shelanski & Klein, 1995). The issue of substitution of input factors is considered in the infrastructure category. By definition, everything that increases productivity can be seen as a substitution of input (ibid.). Being at the beginning of the value chain, the production of hydrogen through electrolysers or the provision of it through a comprehensive supply network both represent important input factors. Therefore, the build-up of necessary infrastructure is tied to the substitution of input. Lastly, the acquisition of knowledge is split into the categories research and know-how as well as corporate partnerships. Knowledge can be understood as the capability to efficiently carry out processes (ibid.). Research and know-how covers knowledge about the technology and its production processes, whereas corporate partnerships refer to the idea of external firm-learning through collaboration along the value chain.

4 Results & Analyses

The following chapter presents the results of the qualitative and quantitative analysis. The subchapters represent the different categories that were developed in the deductive content analysis and reflect on current starting points for hydrogen market ramp-up. They are separated into a broader macro and a micro perspective that entail firm specific requirements. The path to market maturity with cost reductions explained through the idea of experience curves is at the center of the analysis.

4.1 Macrolevel Perspective

In this subchapter, the two categories infrastructure and market mechanisms shall be analyzed. This is done by generating insights from qualitative expert interviews, complemented by additional quantitative results.

4.1.1 Infrastructure

In the first phase of energy transition, attention was predominantly on the expansion of renewable power production. Renewables, however, are dependent on weather conditions and lack the capability to steadily provide energy which is why "[…] base load capability of renewables can […] only be ensured with hydrogen" (Expert 1). The importance of hydrogen infrastructure for the development of a hydrogen economy is highlighted by practitioners and researchers alike (Bain & Company, 2021; Meyer & Winebrake, 2009). Therefore, the question of necessary infrastructure was raised in expert interviews and the results are displayed in the following table:

Aspect	Scale	No. of Interviewees	Percentage
Relevance	High	4	40
	Medium	4	40
	Low	2	20
Location Factor	Domestically	0	0
	Globally	0	0
	Combination of Both	10	100

Table 2. *Category Infrastructure; Source: Own Data*

Table 2 provides an overview of the insights that indicate a mixed perspective on the relevance of infrastructure for hydrogen development. One interview partner, for example, opined that the "[…] question of infrastructure has been solved for the time being by regulating the relevant grids" (Expert 8). In contrast, other experts argued that there is still ongoing need for infrastructure expansion. This is due to the fact that consistent availability of energy commodities is "crucial because it goes in the direction of security of supply and companies […] do not like to live with supply bottlenecks" (Expert 3). Experts highlighted the fact that "green electricity […] is where limitations lie" when it comes to infrastructure of hydrogen and its associated costs (Expert 5). To examine whether the effect of renewables significantly impacts the hydrogen costs, a regression analysis compared daily green hydrogen prices and renewable capacities shown in Appendix 5. The results implicate a statistically significant relation between the dependent variable of green hydrogen costs and the independent variable of renewable capacities. The analysis shows that additional renewable capacity can lower the costs of green hydrogen which aligns with the statement of Expert 5 who emphasized the need for green electricity expansion to reduce costs of green hydrogen.

Apart from expansion and infrastructure development, the question of where infrastructure will be built was also raised in the interviews. Creating a global hydrogen industry that includes countries with excess capacities of renewable energies has raised attention (Brändle, Schönfisch & Schulte, 2021). The interview results show unanimity that hydrogen will not just be produced domestically but rather traded on a global scale. This is because in many countries domestic production "[…] will have its limits where [countries] just cannot build more or it becomes too costly again, so they have to procure it globally" (Expert 4). In contrast to currently used energy sources, hydrogen will not be traded to the same extent, "[…] because there will be fewer countries, apart from Japan and countries in Europe, that will have a major need for hydrogen imports" (Expert 8).

Policy makers have set regulatory requirements incentivising the development of a market. It has become the common interest of energy producers and policy makers to collaborate on accelerating energy transition (Meckling, 2019). This process can also be observed for hydrogen with many governments around the world stepping up efforts to build a global hydrogen infrastructure (European Commission, 2020). Hence, public and private agents are interdependent. While stronger regulatory requirements cause increasing managerial commitment to energy transition, policy measures must also reflect the current composition and specificities of the industry (Hartmann, Inkpen & Ramaswamy, 2021; Salamon & Siegfried, 1977). While there is now "[…] consensus between politicians and energy producers about the importance of hydrogen", the coordination of political and private tasks in this field remains unclear (Expert 8). Thus, Expert 4 suggests the following distribution of tasks:

> *"Building infrastructure sits best on the investor side since there is the knowledge, expertise and know-how. The role that policy plays is more economic, providing tax incentives, fixed quotas and determining location factors to steer the behavior of energy producers."* (Expert 4)

4.1.2 Price Building

Usually, price building of energy commodities is done via a market that brings together market players and determines price according to supply and demand (Li et al., 2015; Williamson, 1979). In the case of hydrogen, there is no established market to date which hampers market ramp-up and price building. Instead of comprehensive trading with multiple market players in competition, hydrogen deals are exclusively negotiated bilaterally. Although there are no concrete price building mechanisms yet, experts expect them to develop in the future:

"The prices that can be found are all artificially calculated but do not follow any market mechanisms. They should therefore be seen as indicators, but a real price will come as volumes ramp up." (Expert 2)

Therefore, the relevance of the category price building and the variables influencing price were highlighted in the interviews and are shown in the table below:

Aspect	Scale	No. of Interviewees	Percentage
Relevance	High	2	20
	Medium	8	80
	Low	0	0
Influencing Variables	Regulation	4	40
	Primary Energy Prices	6	60
	Lack of Market Mechanisms	8	80

Table 3*. Category Price Building; Source: Own Data*

The results presented in Table 3 show a medium to high importance associated with creating a market structure with transparent price building mechanisms. A reason is that "in the long term all companies want to be able to buy hydrogen as a commodity from a market with different suppliers, […] that will not happen so quickly" (Expert 6). It is expected that hydrogen costs will not reach breakeven before the end of the decade (Hydrogen Council, 2021). Thus, factors that could potentially lower costs were discussed in the interviews. As mentioned in the prior subchapter, hydrogen is a secondary energy source which is why the marginal costs of production are determined by costs of primary energy. Apart from this, the path to breaking even can be accelerated with further tightening of regulatory requirements on fossil fuels through CO_2 taxation (Longden et al., 2022). Increasing prices of GHG intensive energy sources makes switching to green hydrogen more attractive and offers "[…] a great lever to raise the demand for green hydrogen" (Expert 3). The most frequently mentioned factor, however, was lack of market mechanisms. Research in the past has shown that transaction costs tend to arise in the transition phase of technologies or economies when market mechanisms have not yet been developed (Meyer 2001). According to Mundaca et al. (2013), higher transaction costs are also observed in the adoption of sustainable energy technologies. The transaction costs of hydrogen are dependent on infrastructure, the price of the commodity itself, the frequency of trades and uncertainty of the market environment (Williamson, 1981; Williamson, 1979). As hydrogen requires heavy investment into infrastructure and specific human knowledge and capabilities, hydrogen is highly asset-specific (International Energy Agency, 2021). Secondly, the hydrogen market is still a "[…] bilateral market, so it requires more players on the market […]" to increase the commitment and frequency of trades (Expert 5). Thirdly, experts observed an uncertain market environment leading to the fact "that many players are still very cautious about spending money." (Expert 8).

To lower the transaction costs, market mechanisms need to be developed to decrease uncertainty. This requires solving the chicken-and-egg problem that exists because demand cannot develop due to a lack of supply and vice versa (Melaina, 2003). The simultaneous boosting of supply and demand is essential for ramp-up of hydrogen. Policymakers must institute regulation to avoid market failure before proper mechanisms have been established (Newborough & Cooley, 2020) An example is legislation by the German Government (2021) to create a government body as a market intermediary to hedge supply and demand. Furthermore, for energy producers to increase supply, they need end consumers of hydrogen to adapt infrastructure as well. Hence, public players are asked to support stakeholders from downstream industries such as chemicals, transportation or the heating sector to nudge their willingness to procure hydrogen resources (Newborough & Cooley, 2021). However, without further commitment from energy producers and end consumers alike, the transition towards a hydrogen economy will not succeed (International Energy Agency, 2021). The notion of alleviating uncertainty in the market for hydrogen producers through managerial activities is discussed in Chapter 4.2.3.

4.2 Microlevel Perspective

In this subchapter three categories -- capital allocation, research & know-how and corporate partnerships -- shall be analysed using the qualitative expert interviews to assess the importance of various categories that influence hydrogen becoming market mature.

4.2.1 Capital Allocation

The importance of capital allocation for energy transition in general, and hydrogen in particular, has been extensively discussed (McKinsey, 2022; Goldman Sachs, 2022). CAPEX needed for building up direct hydrogen supply chains is estimated to be in the order of $5 trillion globally, but only a small part of this has been deployed as of now (Goldman Sachs, 2022). Investments have mainly been made in renewable electricity generation, but for the energy transition to succeed investment must be made in technologies that lower CO_2 emissions, including hydrogen. The experts pointed out that energy transition now has greater complexity because after the "first step [of] the transition of mainly primary energy sources, the question of secondary energy production is on the table [now]" (Expert 3). The transition of heavy industrial processes in "hard-to-abate-sectors" is difficult due to the lock-in effects of "[…] heavy industrial processes that have been established for such a long time" (Expert 4). With capital allocation towards hydrogen projects, industrial processes can be converted to phase out fossil fuels and instead use energy sources with lower CO_2 emissions. To understand capital allocation pertaining to hydrogen, the current availability of capital was addressed by the experts. The results of that are shown in the table below:

Aspect	Scale	No. of Interviewees	Percentage
Relevance	High	1	10
	Medium	5	50
	Low	4	40
Capital Access	Scarcity	8	80
	Sufficient Access	2	20

Table 4*. Category Capital Allocation; Source: Own Data*

As shown in Table 4 most experts pointed to a scarcity of capital. While some experts argued that due to many hydrogen projects being launched "it can be assumed that the attractiveness of investing in hydrogen projects is high" (Expert 7), others opined that investors "are still very cautious about spending money" (Expert 8). This reluctance is explained by hydrogen "still [being] a nascent market, so the number of players that can get their head around the risk given the amount of uncertainty in the market is still fairly low" (Expert 4). Being at the threshold of commercialization, investors believe "the longer you wait, the cheaper the investment is expected to be, giving […] an incentive to hold back their investments" (Expert 8). To unlock further capital, energy producers and institutional investors demand political engagement which means "[…] state intervention in the form of clear guidelines, on the basis of which the companies then have planning and investment security" (Expert 6). This reasoning is shared by institutional investors who argue that wider adoption of hydrogen can only be ensured through a variety of direct policy support mechanisms as well as indirect incentives through raising CO_2 taxes (Goldman Sachs, 2022). Another point that was put forward by experts is the need to create a common taxonomy of what green hydrogen actually is. To date, "the definition of green hydrogen" remains unclear and needs to be determined to define "what constitutes green hydrogen" (Expert 7 & Expert 9).

While policymakers are asked to set regulatory standards, energy producers can foster capital allocation by improving competitiveness through cost reductions. This perspective of unlocking capital through profitability was brought up by a private equity manager who stated that "as investors we need an optic into the size of the market to ensure that we see returns and what helps for that is obviously price; but currently there are still many investors waiting until the price becomes x Dollars" (Expert 4).

To provide an idea of how capital allocation can influence the technology expansion, the example of the renewable energy market ramp-up in Germany is below.

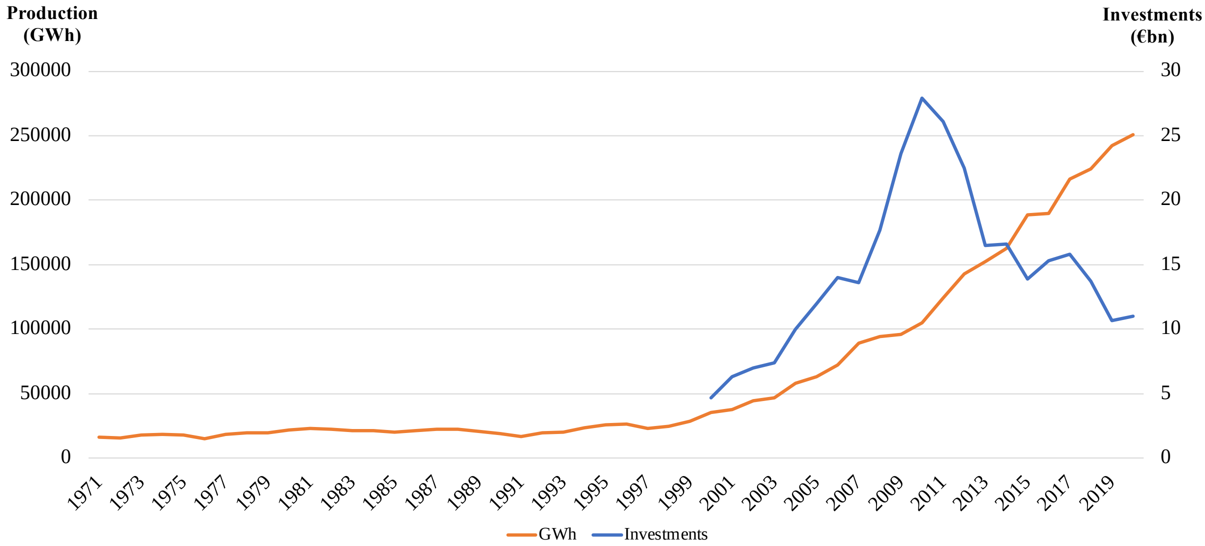

Figure 6. *Renewable Market Ramp-up; data retrieved from International Energy Agency, 2022; Renewable Energies Agency, 2022*

The graphs show that after a steady development of renewable production until the beginning of the 21st century, the production capacity expanded after investments were increased. In recent years, the investments decreased significantly, however the trend of capacity expansion continued. This indicates that capital allocation is especially important at the beginning of a ramp-up phase.

4.2.2 Research & Know-How

The lack of competitiveness of hydrogen vis-à-vis other energy sources has been mentioned throughout this study. Apart from barely existing infrastructure, costs are still too high and can therefore not compete with fossil alternatives. Experts consider that the issue is "[…] not related to technology or physics" (Expert 1). Instead, they "[…] still [see] a lot of room for maneuver in this technology, because there is certainly great potential to reduce costs […]" because "[…] hydrogen production costs will decrease over time and with technological progress" (Expert 5; Expert 7). The importance of enhanced research and know-how and understanding potential levers to reduce costs were discussed by the experts. The results are shown in the following table:

Aspect	Scale	No. of Interviewees	Percentage
Relevance	High	2	20
	Medium	6	60
	Low	2	20
Experience Levers	Technology	4	40
	Production	9	90
	Infrastructure	6	60

Table 5*. Category Research & Know-how; Source: Own Data*

The results in Table 5 show divided opinion with most experts assigning medium importance to these factors. In terms of the levers where further research and knowledge gain can lead to cost reductions, four experts indicated that cost reduction can be achieved through further technological advances. The issue of transporting and storing hydrogen in different physical states is difficult because "the problem entails liquifying hydrogen which prefers to be in a gaseous state" (Expert 3). Recent research estimates the lifecycle efficiency of hydrogen produced through electrolysis to be at approximately 30% (Burton et al., 2021). Therefore, "innovation and production processes [are needed], especially if you look at efficiency levels" which is why new electrolysis technologies can offer potential cost reductions (Expert 9).

The second lever mentioned was infrastructure. In comparison to other energy production methods, setting up hydrogen infrastructure requires significant investment (Agnolucci, 2007). The creation of a global hydrogen economy with the necessary transportation, storage and conversion technologies requires considerable effort on the part of energy producers and capital providers. One expert noted that "the investment costs for electrolysers have a strong influence" on hydrogen costs (Expert 7). Depending on production capacity and region, capital costs are estimated to determine between 20 to 40 percent of total hydrogen costs (Fan et al., 2021). Addressing this, Böhm et al. (2020) show that an increase in production rates triggered by technological learning can significantly reduce the capital costs and help to make hydrogen more viable and competitive.

Scaling production was brought up by 90% of experts highlighting that "[…] scaling and learning curves are the panacea when it comes to hydrogen becoming economical" (Expert 3). In the report by the Hydrogen Council (2021), strong potential cost savings are emphasised through economies of scale. The authors specifically mention that the learning rate has been low compared to other low-carbon technologies. Steeper learning curves could thus produce additional savings (ibid.) The highest share of the LCOH, however, lies with primary energy costs with "about 70% of the costs […] currently accounted for by the input energy" (Expert 9). Therefore, and as stated in Chapter 4.1.1, energy producers need to expand renewable energy capacities to ensure available green and cheap electricity. Policymakers can support this through market ramp-up but also through regulatory requirements that increase the attractiveness of hydrogen vis-à-vis fossil fuels (International Energy Agency, 2021). Raising prices of global fossil fuels and increasing ETS allowances would create pricing pressures thereby leading to a break-even for green and grey hydrogen by 2030 (Goldman Sachs, 2022). However, experts assumed the need for long-term support by public entities and "[…] subsidies for a long time in order to make hydrogen competitive at some point" (Expert 10).

4.2.3 Corporate Partnerships

The pace of hydrogen expansion has recently accelerated with several corporate partnerships being developed (ExxonMobil, 2022; RWE, 2021; Shell, 2020) What they all have in common is connecting energy producers with other entities from different stages in the value chain. Energy transition requires not only additional knowledge, capital, and capacity expansion, but also demands new value chains to transform energy as an important input factor for industrial processes (Eitan et al., 2019). Relevant corporate partnerships for ramp-up were discussed by the experts with the following results:

Aspect	Scale	No. of Interviewees	Percentage
Relevance	High	2	20
	Medium	6	60
	Low	2	20
Motives	Coordination	3	30
	Know-how	3	30
	Risk-spread	6	60
	Other	2	20

Table 6*. Category Corporate Partnership; Source: Own Data*

The findings show inconsistent expert opinions. Mostly, they attributed medium level reliance to corporate partnerships for hydrogen development. The question of fostering coordination and know-how was raised equally by all the experts. As explained in Chapter 4.1.2, the ramp-up of hydrogen is impeded by the chicken-egg-problem. The motive of enhanced coordination was mentioned by 30% of experts. Bringing together producers and consumers facilitates creating and coordinating supply and demand simultaneously, which is why one expert stated:

> *"The three legs of the system, production, consumption, and distribution must be built simultaneously and in a coordinated manner. If this coordination is not successful, you have incoherence and then a link in the hydrogen chain is missing."* (Expert 2)

Distributing risks was mentioned by 60% of the interviewees as a key motive for setting up corporate partnerships. Building infrastructure requires enormous capital allocation which is why one interviewee stated:

> *"It's about solving the chicken and egg problem because no one wants to invest without having security on the other side. In fact, as far as I know, the perspective is that investors are cautious because they are afraid of 'stranded investments'. These partnerships create mutual dependencies, which can spread the risk."* (Expert 8)

When setting up infrastructure, business collaboration is important as partnerships allow dispersion of risk factors among various counterparties (Melese et al., 2017). Partnerships not only share financial risks but also increase the knowledge base, especially in environments with complex technologies that implicate different aspects of the value chain (Hagedoorn, 1993). Other motivations indicated by experts included "[…] leveraging the strength of both partners" to increase the knowledge base (Expert 4).

Besides private partnerships discussed above, public agents can engage in partnership building as well. This is particularly effective for cross-national partnerships for commodity procurement (Rosell & Saz-Carranza, 2020). Establishing global hydrogen partnerships that create supply, along with procurement chains, can support private agents in their pursuit of developing a comprehensive market (von der Leyen, 2022).

4.3 Interdependence Perspective of Public and Private Agents

The experts differed on the necessary domains of action required for hydrogen ramp up. To better understand the importance of the five categories, experts were asked to rank them from high to low. The average rankings are shown below:

Interviewee Category	Infra-structure	Price Building	Capital Allocation	Research & Know-how	Corporate Partnerships
Private (n = 3)	3.33	3.33	2.67	3.00	2.67
Public (n = 4)	2.5	2.5	3.75	3.00	3.25
Research (n = 2)	3.00	3.5	3.5	1.5	3.5
Overall n = 9 (excl. 1 N/A)	**2.89**	**3.00**	**3.33**	**2.67**	**3.11**

***Table 7**. Average Category Ranking; Source: Own Data*

The results in Table 7 do not provide for a clear picture of the nuances of the categories with only small differences in the mean rankings. Overall, the results suggest higher importance for infrastructure build-up and cost reductions through enhanced research and know-how. In accordance with research question *1b* that seeks to examine the interplay of public and private agents during the ramp-up process, different interviewee categories were created. The results point to public agents assigning greater importance to infrastructure and price building measures. Private agents, on the other hand, perceive capital allocation and partnership building to be more relevant. Experts from a research background believed that research & know-how activities are most significant. Due to the small sample size of $n = 9$ these results should, however, only be seen as an indication. To validate these results, findings were compared to existing literature on energy transition.

Notwithstanding the small sample size, these results seem aligned with existing research. It was found that lack of policy engagement can create an economic barrier for infrastructure development (Reddy & Painuly, 2004). In the past, policymakers have also dealt with market ramp-ups of other energy sources and addressed market failures by managing negative externalities through an emissions trading (Pollitt, 2012). This confirms the role of public policy for hydrogen to achieve market maturity and the fact that regulatory interventions are needed during the ramp-up phase (Schlund et al., 2021). Regarding capital allocation, the International Renewable Energy Agency (2018) finds that up to 90 percent of the investment required can be satisfied by the private sector. Furthermore, corporate partnerships can improve cost-benefit metrics through collaborative projects (Eitan & Fischhendler, 2021).

After implementing these necessary prerequisites, we can envisage hydrogen adoption gradually scaling successfully. These effects will, however, start off slowly until hydrogen technology reaches a critical state, supply and demand increase, and at the same time prices and costs are lowered significantly (Ball & Weeda, 2015). The process of the system reaching this critical state can be reached if public and private agents take concerted actions which will be discussed further in the next chapter.

5 Discussion

In this chapter, the results from the previous chapter will be related to the three research questions. Those findings shall be used to provide managerial implications for companies and political stakeholders. The limitations of this study are also presented with suggestions for future research.

5.1 Experience Curves: Recommendations for Public and Private Agents

Throughout this analysis the dimensions of experience curves needed for hydrogen to become a market mature alternative were discussed. These included (1) initiation of investments, (2) elimination of waste, (3) substitution of input factors and (4) acquisition of additional knowledge. It was found that energy producers and policymakers are key stakeholders due to their strong influence enabling cost reductions. By aligning public and private behavior, the system can achieve a critical state to allow hydrogen to scale as an emergent phenomenon. The analysis highlights the interdependence of the different categories in the system, which is why experts were not able to provide a uniform opinion on levers to be prioritised for hydrogen to ramp-up. However, the results suggest that to some extent burdens must be shared by public and private agents in the system.

(1) According to the experts, initiating investments is important to build necessary infrastructure and to scale supply and demand to eventually create a comprehensive commodity market (Expert 6). However, there is still uncertainty in the market which is why investors are hesitant to ramp-up investments (Expert 4), a notable characteristic of complex systems. This uncertainty mainly derives from lack of market structures, especially regarding the unknown capacity of entities that will supply hydrogen (Nunes et al., 2015). Hence, investors do not know if their *ex ante* investments will pay off. Experts therefore suggest strong policy intervention to mitigate uncertainties and enable deployment of capital on a larger scale (Dolfsma & Leydesdorff, 2009).

(2) The elimination of waste refers to any effort that does not add value including wasted time or costs (Henderson, 1984). Due to the lack of an efficient market, transaction costs and frictions create difficulties for matching supply and demand (Williamson, 1979). The chicken-and-egg problem already alluded to must be resolved (Melaina, 2003). Private agents can try to overcome this by forming partnerships with other agents along the value chain to create stable business relationships (Expert 2). Public agents need to support the development of market mechanisms by defining a clear regulatory environment and incentivizing buyside and sellside actors as well as creating subsidies for operational expenses and CAPEX (Expert 1; Expert 8).

(3) Energy sources are at the beginning of industrial value chains which is why many agents in the system adapt their infrastructure to a singular energy source. The transition from fossil fuels

to hydrogen can therefore be seen as a crucial substitution of input factors when it comes to reducing CO_2 emissions. Hence, a large number of industries must adjust their business models (Trapp, Voigt & Brem, 2018). The challenge is to overcome underlying lock-in effects, which presently explain the rather slow development of hydrogen (Pantaleone & Fazioli, 2022). The transition to hydrogen means breaking reliance on fossil fuels for energy transition to proceed and hydrogen helps solve the storage problem associated with renewables (Stöckl & Zerrahn, 2020). Experts indicated that the infrastructure upgrades are to be executed by private agents, however public agents have a strong role when it comes to laying the groundwork for structures of a global hydrogen economy (Expert 4; Expert 9).

(4) The acquisition of additional knowledge is key for increasing the efficiency of hydrogen and allowing for production scaling. Large cost reductions can be achieved when electrolysers are produced at a higher scale (Expert 5). Due to uncertainty, investors refrain from supplying funding needed to reach a critical state at which production would increase exponentially. This, however, is necessary for bringing costs down (Expert 3). Private agents respond by forming partnerships and expanding their investments in infrastructure and research (Expert 2). Public agents are asked to support the process of scaling through policies that develop a global market. Moreover, they can subsidize infrastructure CAPEX to prevent costs being passed on to end customers (Roland Berger, 2021).

Henderson (1984) understands the concept of experience curves as a strategic tool to break up complexities associated with cost reductions. In the case of hydrogen "[…] experience curves are the panacea when it comes to becoming economical" (Expert 3). Therefore, experience curves are an appropriate tool to guide the path towards market-maturity and to coordinate necessary actions of public and private agents.

5.2 Complex Systems: Reaching Market-Maturity

The claim presented in Chapter 2.2 is that the energy industry is a complex system, a matter corroborated by this study. Many experts indicated that there is numerosity of influencing agents in the system with strong interdependencies between them (Expert 3; Expert 9). Due to these interdependencies, the path to market maturity is strongly influenced by interactive behavior of public and private agents. Change-making actions within the categories discussed throughout Chapter 4 are not always distributed equally between public and private agents.

However, effects only unfold if measures are coordinated to create positive feedback loops (Meckling, 2018). The following illustration shows how different market maturity levers are dependent on public and private interactions, as well as upon interactions with each other:

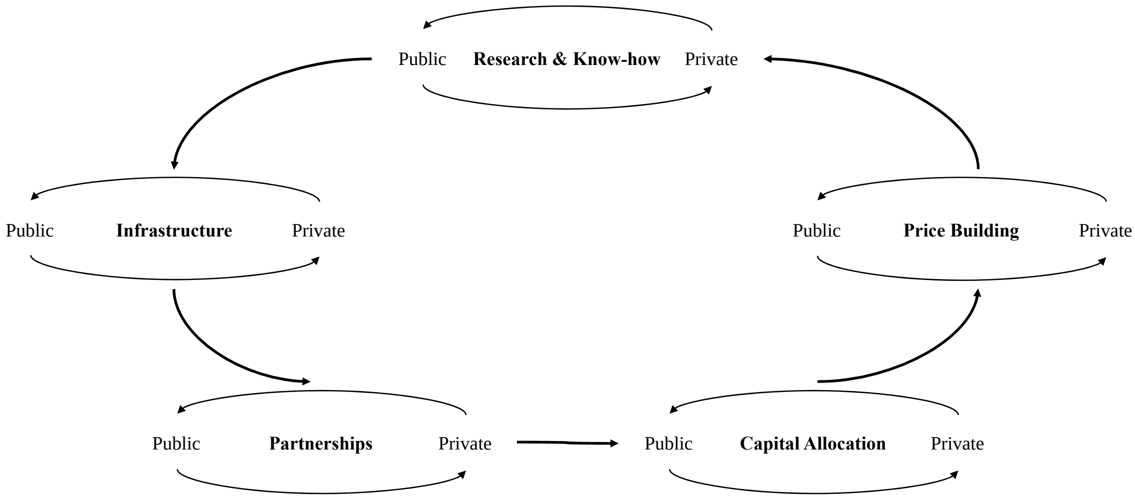

Figure 7. *Lever Interdependency Loop*

Figure 7 illustrates that levers are not only influenced by the actions taken by public and private agents but are in a reflexive relationship with other levers. Therefore, the path to market maturity is a loop of several individual interacting feedback loops that must be understood systemically.

Complex systems are characterized by self-organizing agents who seek to align themselves with their environment. This raises the question of whether agents' desire for adaptation to environmental surroundings can be shaped by exploiting inherent hierarchies (Cilliers, 2001). Research has shown that energy producers are committed to constant self-organising alignment with their regulatory surroundings (Hasanov & Zuidema, 2018). The research of this thesis reinforces the idea of 'viable coordination' guided by public agents (Witt, 1997). In contrast to natural complex systems, economic ones are able to respond to the hierarchically generated cues (Aghion et al., 2016). This aligns with the findings of this study as experts argued for strong policy intervention to catalyse market ramp-up towards a critical state where hydrogen adoption shifts from slow to exponential growth (Expert 3). This path towards a critical state is illustrated in the following graph:

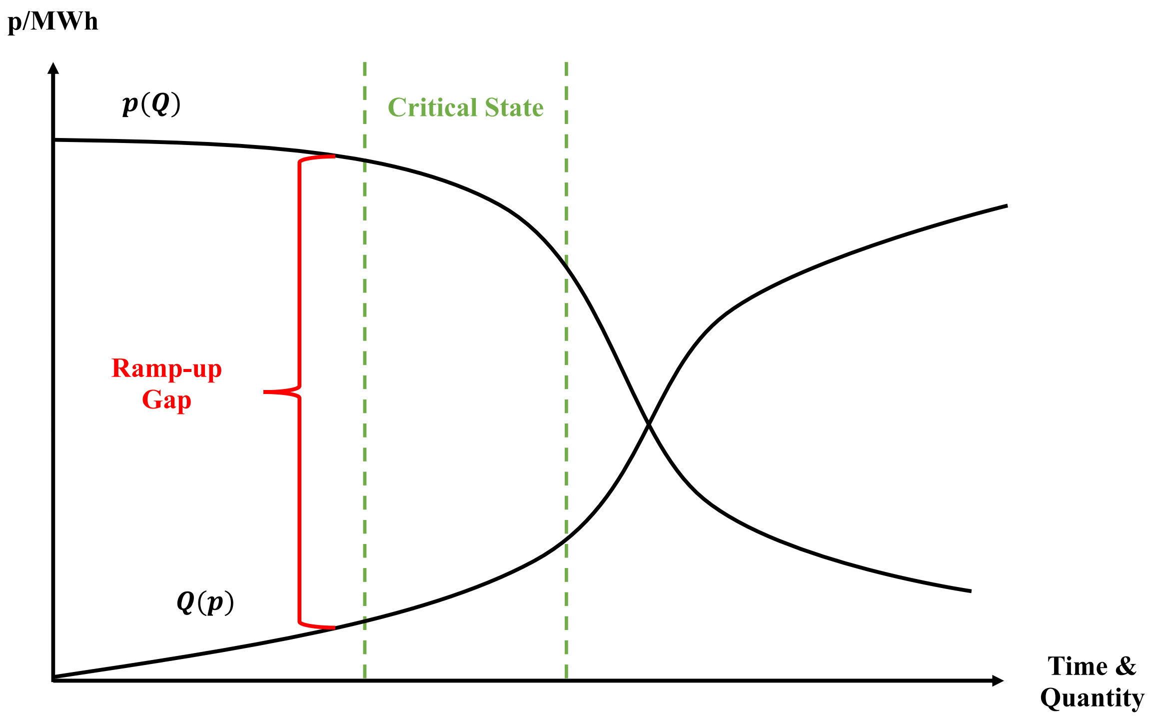

Figure 8. *Power Law Trajectory of Market Ramp-up; adapted from Gan, Eskeland & Kolshus, 2007*

Figure 8 suggests that the market ramp-up follows a power law with supply and demand slowly taking off until they reach a critical state. To accelerate the development, public and private agents must bridge the ramp-up gap to reach the critical state where self-developing market mechanisms come into effect. Hereby, the market develops a momentum, which causes a rapid convergence of the existing discrepancy between supply and demand (Gan et al., 2007). This can be explained by the non-linear and interdependent effect mechanisms that are caused through mutually reinforcing feedback loops as shown in Figure 7. Gore (2022) shares the opinion that traditional Gaussian causal models are no longer suitable for describing relationships in today's increasingly complex systems. This is supported by the example of the ramp-up of renewable energy capacity, which also followed an exponential developmental pathway, as depicted in Figure 6. It can be concluded that power laws are a valuable vehicle to study future transitions and other macroeconomic developments (Gabaix, 2016). The application of power laws is more suitable to describe effect mechanisms as various examples of complex systems display Pareto distribution characteristics (Gore, 2022).

The seemingly slow adoption of a new technology in a complex system can be accounted for by the long chains of adjustments needed before the system exhibits change. This inertia forces public and private agents to intensify their efforts when seeking change in an economic complex system (Hannan & Freeman, 1984). In a similar vein, findings suggest that the path to market maturity is a result of interactions between different agents creating mutually reinforcing feedback loops, which bring about factors, such as cost reductions, that take the system to a critical state where change occurs.

5.3 Repercussions of the Emergent Phenomenon Hydrogen

The literature presented in Chapter 2.4 leads us to anticipate hydrogen becoming an emergent phenomenon. Throughout the analysis, experts described the importance of hydrogen for the energy industry as a whole, and how it has to the potential to fill a gap associated with energy transition, especially in sectors where CO_2 abatement is difficult (Expert 4). The question of embracing hydrogen as widely used energy source only emerged in recent years when policymakers and energy producers realized that energy transition will not succeed without a secondary energy source (Expert 3). In the analysis here, numerosity, non-linearity and connectivity of relationships were shown through the interactions of public and private agents for different levers oriented towards enabling market maturity. Furthermore, analysis revealed self-organizing behavior of agents, with policymakers providing orientation for other agents in the system to adapt themselves. Therefore, hydrogen should be seen as an emergent phenomenon. It is also a piece of the puzzle in the overarching moves towards energy transition. Mintzberg & Waters (1985) distinguish deliberate from emergent strategies. According to this differentiation, energy transition can be seen as the long-term deliberate political and managerial strategy to make energy production sustainable. Incorporating hydrogen in energy transition can be characterized as an emergent phenomenon that is shaping tactics into emergent strategy, as the need for CO_2 reductions in industries becomes more pressing.

Goldstein (1999) studied interdependencies and inter-agent dynamics in the presence of emergence. Following his lead, this analysis sought to understand complexity by studying the emergent characteristics of hydrogen in the complex system of the energy industry as a whole.

5.4 Managerial Implications for Development of Hydrogen

In light of the emergent characteristics of hydrogen that were disclosed throughout this thesis, certain managerial implications arise. To reach market maturity efficiently, burden sharing between public and private agents was shown to be needed. Where public agents are asked to facilitate necessary infrastructure as well as proper market mechanisms to enable price-building, public agents are called upon to allocate further capital towards hydrogen projects. Distributing tasks and risks in a way that lowers uncertainty will help to accelerate the process of reaching a critical state where growth becomes exponential. Measures from both, public and private agents, should be directed towards creating positive feedback loops to promote self-development. To manage the self-organizing nature of complex systems and their associated inertia, the results of this study suggest developing forms of viable coordination. Public agents must set regulatory specifications to which private agents can adapt. In a nascent market where chicken-and-egg problems occur, coopetition can help to resolve this dilemma (Brandenburger & Nalebuff, 1996). In the case of hydrogen, corporate partnerships can ensure that developing a hydrogen economy takes place along the value chain and thus supply and demand are simultaneously stimulated.

This study has concluded that the development of hydrogen is to be perceived as an emergent phenomenon creating pressure for public and private agents to act. Firms in the energy sector as well as in CO_2-heavy adjacent industries are asked to adapt their business model to this development to avoid being forced out of the market. Public agents are primarily concerned with achieving the goals of the energy trilemma. Here, too, adapting to hydrogen is of strategic importance to make this trilemma future-proof. National economies as well as businesses can achieve a competitive advantage when being first movers in embracing a new technology. In complex systems which are subject to constant dissipations, the transition follows a recurring cycle of adaptive change (Hurst & Zimmermann, 1994). Connecting this to the concept of Mintzberg & Waters (1985), it can be argued that realized strategy is the result of consecutive adaptive life cycles triggered by gradually emerging phenomena. Energy transition will cause ongoing change in the energy sector for the foreseeable future. Thus, public and private agents should be prepared for adapting to change to retain competitive national or corporate competitive advantage.

5.5 Limitations

To evaluate the results, a brief quality assessment is provided and finally a short outlook for future research is proposed.

5.5.1 Quality Assessment

To avoid biased results in qualitative research, Hammarberg, Kirkman & de Lacey (2016) stress the need to incorporate quality assurance by assessing (1) trustworthiness, (2) consistency, (3) applicability and (4) credibility of the research design.

(1) Trustworthiness is given through robust and explicit data generation methods that create transparency (ibid.). To ensure this, the expert interviews followed a semi-structured approach with experts from different fields. By bringing in experts from different backgrounds, the findings reflected contradictory opinions to avoid potential biases. Nevertheless, results can still be skewed due to the selection of experts and a consequent researcher bias (Noble & Smith, 2015). (2) The reliability of the finding can be checked for consistency by examining other similar research which should reach analogous conclusions from the data. Therefore, experts were asked to rank the different categories used in the analysis. Due to the small sample size of $n = 9$, the findings are to be treated cautiously. However, one must also note that in complex systems, increasing the sample size does not necessarily yield more accurate knowledge about systemic change since distinguishing signal from noise is an enduring challenge (Höge, Wöhling & Nowak, 2018). Furthermore, experts sometimes were ambiguous which calls into question the reliability of the qualitative analysis. (3) The notion of applicability refers to the idea of transferring findings into other contexts outside the study situation (Hammarberg et al., 2016). Consequently, the findings were placed within the broader context of research on complex systems. (4) Credibility can be provided through reflexivity to ensure necessary internal validity of the data and to avoid scholars' biases (ibid.). To this end, learnings from the overarching energy transition movement were brought into the discussion to see if results were credible in light of learnings derived from other stages of energy transition.

5.5.2 Research Outlook

This research began in February 2022 before the war between Russia and Ukraine began. The war's geopolitical upheaval has led to radical shifts of well-established policies, including global energy policies (Nature, 2022). The research of this thesis does not consider the repercussions of the war on the energy transition and the ramp-up of hydrogen. Furthermore, the European Commission (2022) outlined key regulatory specifications for ramping up the hydrogen market. The effects of these two events are not included in this analysis, but are likely to influence hydrogen development moving forward. Hence, the changing macro environment is a fertile area for additional research in this field.

To reduce complexity, the focus of this study was placed on interactions between policymakers and energy producers. For a more comprehensive understanding, additional stakeholders introduced by Schlund et al. (2022) could be brought into the discussion. The analysis combined qualitative expert opinions with insights from the ramp-up of renewable energies. These findings indicate a power law trajectory. To date however, it remains unclear how widely hydrogen will be used. Under the assumption of exponential development of hydrogen, different application scenarios listed in Quarton et al. (2020) can be used to calculate alternative ramp-up pathways, bearing in mind power law trajectories. In a next step, the development of hydrogen could be analyzed quantitatively with a specific focus on interdependencies and their respective second and third order effects through different forms of time series analyses (Shalizi, 2006).

6 Conclusion

This research used complex systems theory to study the steps necessary for hydrogen to gain market maturity. Regarding research question *1a*, different levers for advancing hydrogen as a substitute for fossil fuels were discussed. The analysis has shown that public and private agents working in tandem can promote hydrogen best by sharing burdens and aligning behaviors to create multiplier effects. The research question *1b* raised how collaboration between energy producers and policymakers should be designed. These findings implicate that through viable coordination between energy producers and policymakers, a critical state can be reached where the development of hydrogen shifts from linear to non-linear growth. It was pointed out that due to their hierarchical positions in the system, policymakers are responsible for setting guard rails which all agents in the system can respect. Finally, research question *2* dealt with the impact of hydrogen on the energy industry. The study concluded that hydrogen could become an emergent phenomenon to which the whole industry would then adapt. To retain competitiveness in complex systems, public and private agents shall prepare for recurring cycles of adaptive change. Interdependencies and associated multiplier effect mechanisms are associated with a sluggish ramp-up phase that then takes as exponential growth kicks in when the system has moved to a critical state. Lastly, it was highlighted that hydrogen is part of overarching energy transition. Hence, it can play a vital role in the transformation of 'hard-to-abate' sectors and thus contribute to reaching the goals of the PCA.

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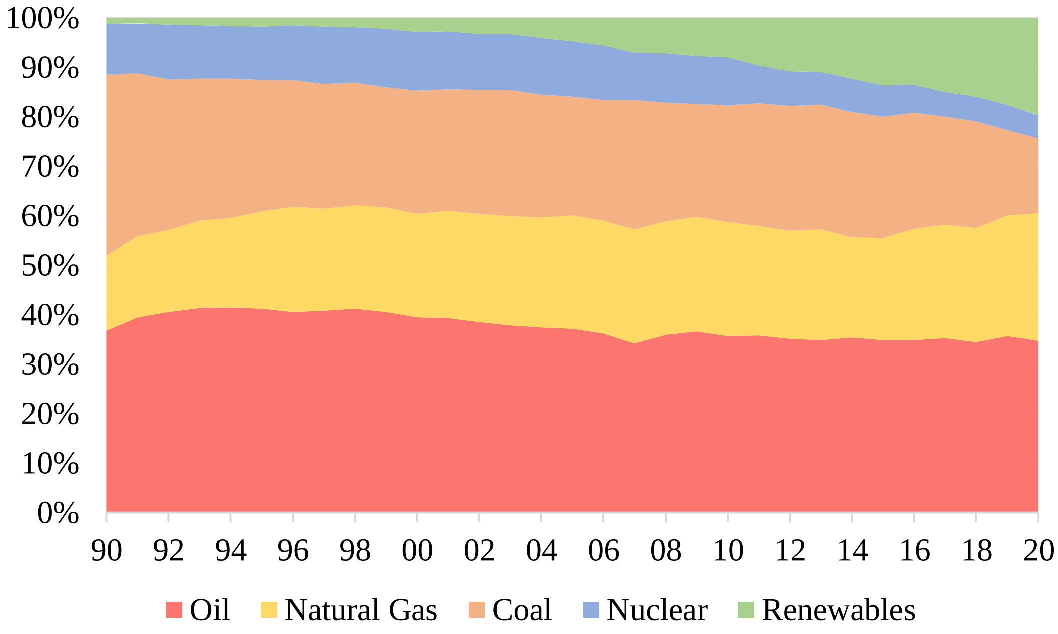
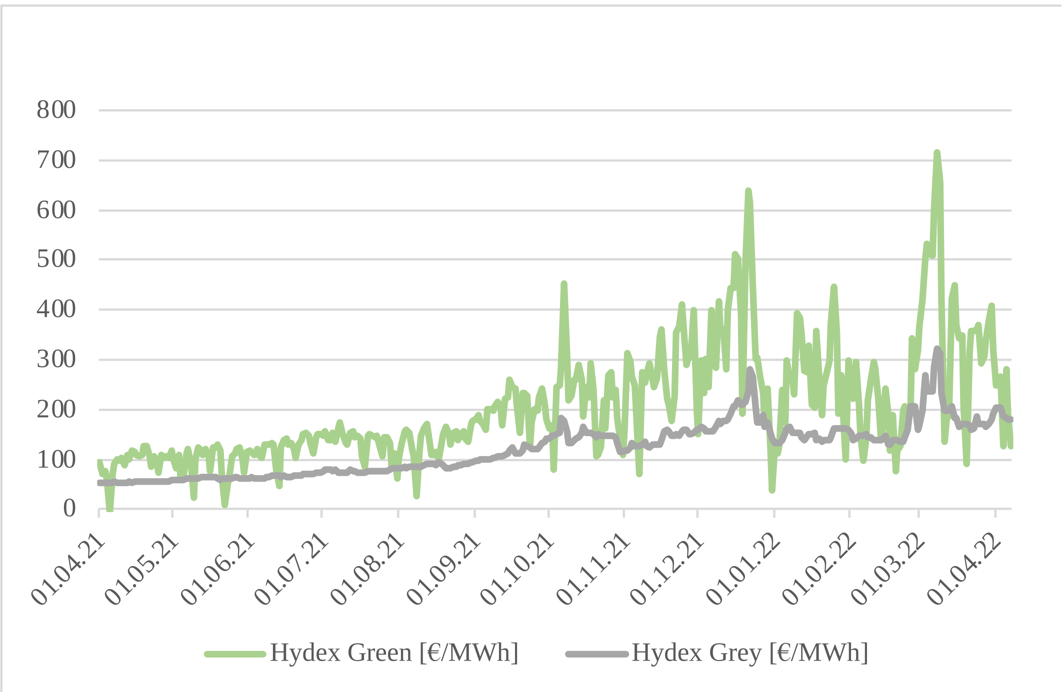
Appendix

Appendix 1



Source: Rubio-Varas & Muñoz-Delgado, 2019; Data retrieved from bp, 2022

Appendix 2



Source: Data provided by E-Bridge Consulting GmbH

Appendix 3

Hydrogen Type	Description	Output
Grey hydrogen	• Produced with energy of fossil fuels whereby significant levels of CO_2 are emitted • Used in the chemical industry for the production of petrochemicals and ammonia-based fertilizers	$H_2 + CO_2$
Blue hydrogen	• Produced in conjunction with CCUS as emitted CO_2 is partly used for steam methane reforming • Allows to cut CO_2 emissions by half compared to grey hydrogen (Burgess, 2021)	$H_2 + CO_2$ (partly exploited)
Turquoise hydrogen	• Produced by splitting gas into hydrogen and fixed carbon through methane pyrolysis • Can be stored or brought back into the production cycle resulting in lower total CO_2 emissions	$H_2 + C$
Green hydrogen	• Produced with renewable energy sources through electrolysis • Allows to avoid carbon emissions by using water and oxygen as alternative reaction components	$H_2 + O_2$
Pink hydrogen	• Produced with energy created through nuclear reactions • Cuts carbon emissions, but is not sustainable as nuclear waste is created which needs to be stored	$H_2 + O_2$ + nuclear waste

Source: Ajanovic et al., 2022

Appendix 4

Questionnaire for Expert Interviews

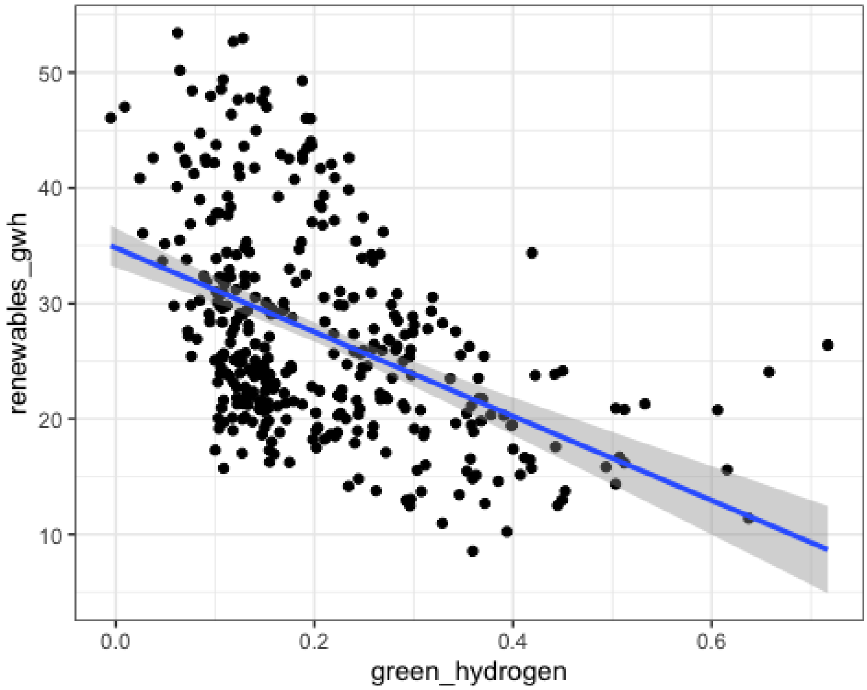
Category	Questions
Introductory Question – Energy Industry & Complexity	1. How will the energy production look like in 10 years and has hydrogen the potential to radically change the energy industry by then? 2. What do you think makes the complexity in the transition of the energy industry? 3. Do you feel that policy makers and energy producers are working in a coordinated way at the moment to embrace hydrogen as an energy source? What needs to be improved?
(1) Infrastructure	4. How is the current demand of investors to invest in hydrogen projects? 5. What policy measures are needed to attract capital allocation towards hydrogen projects? (tax measures, subsidies, etc.?)
(2) Price Building	6. What capabilities must companies acquire in order to embrace hydrogen as a market-mature energy source and how far are they away from achieving this? 7. Can firms expect a learning effect for hydrogen that reduces costs? What are the key points where experience will have a strong effect?
(3) Capital Allocation	8. Currently the hydrogen prices are fluctuating especially for green hydrogen, so what are the reasons for that and how can prices be stabilized in a long-term perspective? 9. Researchers see a chicken-egg problem with supply and demand of hydrogen. How do you see the H2 Global initiative of the German government that hedges supply and demand through long-term PPAs with producers and short-term sales of those hydrogen capacities to overcome this potential chicken-egg-problem? (Contracts-for-Difference)
(4) Research & Know-how	10. What influence does the infrastructure have on the development of the hydrogen economy and what political measures can contribute to the development of the hydrogen infrastructure? 11. Shall energy companies and public players prioritize to set up infrastructure in Europe or focus to invest in countries of the global south where the production costs of green hydrogen are lower? Why?
(5) Partnerships	12. Throughout the last months, a lot of new partnerships between companies in the field of

	hydrogen have been established. How important is this kind of collaboration and what is the most important reason for firms to establish such partnerships? 13. Since there are obviously no real market mechanisms for hydrogen and hydrogen is mainly traded through bilateral deals (e.g. BASF & RWE), is this uncertainty a problem and if yes can it be reduced through such partnerships?
Closing Question – Ranking	14. In which order would you rank these categories if the first rank represents the highest importance for building the hydrogen industry and the fifth rank reflects the lowest priority?

List of Interview Partners [anonymised]

No.	Position	Date	Category
1	Board Member	27.04.2022	Private
2	Product Manager	27.04.2022	Private
3	Head of Department	02.05.2022	Public
4	Director	07.05.2022	Private
5	Senior Project Manager	08.05.2022	Public
6	Project Manager	08.05.2022	Public
7	Project Manager	10.05.2022	Public
8	Research Associate	11.05.2022	Research
9	Research Associate	16.05.2022	Research
10	Project Manager	17.05.2022	Public

Appendix 5



	Dependent variable:
	green_hydrogen
renewables_gwh	-0.006***
	(0.001)
Constant	0.366***
	(0.017)
Observations	366
R2	0.214
Adjusted R2	0.211
Residual Std. Error	0.104 (df = 364)
F Statistic	98.836*** (df = 1; 364)
Note:	*p<0.1; **p<0.05; ***p<0.01

$$Green\ Hydrogen\ Cost = 0.366 - 0.006 * Renewable\ Capacity$$

Interpretation: Every additional GWh of renewable produced electricity decreases hydrogen costs by 0.006€/GWh.

Interview Notes – Expert 1 (27th April, 2022):

Introductory Questions – Energy Industry & Complexity:

- Hydrogen will completely change the structure of the energy producion in the future, because there is simply no other way.
- I see a mistake in the fact that politics says its up to the businesses to do it. They have the politically-given task of protecting the climate, but industry and technology are supposed to find their own ways to do it.
- And for this we need a little more than industry ownership, which is often nothing more than the sum of particular individual interests.
- There is no overarching economic framework on the way to the climate goals.
- Politicians must see the big picture and offer companies the guidelines they need to be able to transform the energy industry.

Capital Allocation:

- We have a funding landscape that is open to technology, but this also leads to bad examples, such as the development of trolley-driven trucks, which wastes valuable research funds.
- We Europeans have a problem with the mindset. We take the view that conventional energies are coming to an end. We know that we need something new and look at what is technically and physically feasible. At the same time, however, we also look at how long we can continue to milk the existing cash cows.

Research & Know-how:

- The problem is not related to technology or physics.
- Institutional investors want to see profit and that comes mainly from the current cash cow. What we need is a real awareness of the need to tackle climate change and therefore prioritise climate protection over business thinking.

Price Building:

- Green hydrogen is not yet taxonomically defined. So the crucial question is from which source it originates and how green it must be.
- Researchers have estimated the costs for different hydrogen production process and can precisely say which prices are needed to become competitive

Infrastructure:

- The important renewable energies are very volatile and unsteady in supply, and in order to compensate for this, we need storage facilities of several TWh, so huge storage facilities that can only be guaranteed by hydrogen or its derivatives.
- The necessary storage and stabilisation of renewable primary energy sources can solely be achieved with hydrogen. The base load capability of renewables can therefore only be ensured with hydrogen.
- Currently, the amount of hydrogen needed has to be multiplied by three to get the same amount of energy - so the efficiency is about 30%. However, this can be increased by the waste heat of the electrolyser.

Partnerships:
- Almost everything that currently comes out of the industry is purely business interests and that means maximising profits. The national economic interest, which is brought in here and there by research associations, is actually only perceived to a limited extent in politics.

Interview Notes – Expert 2 (27th April, 2022):
Introductory Questions – Energy Industry & Complexity:
- The necessary condition for the development of the hydrogen economy is the joint action of producers, operators & suppliers and customers.
- Policy measures that create an attractive competitive field vis-à-vis fossil energy consumption through incentives are important for the development of hydrogen.

Capital Allocation:
- There does not seem to be a lack of money, if you can observe that there are many hydrogen projects and even the first IPOs of hydrogen companies can be observed.
- It is clear that hydrogen and the development of a hydrogen economy is very capital-intensive. The construction of a hydrogen dispenser, for example, costs between 2 and 3 million euros.

Research & Know-how:
- It needs engineering knowledge, innovative strength, but also simple things like knowledge about electricity and gas and of course the ability to trade it.

Price Building:

- There is currently no market for hydrogen. The prices that can be found are all artificially calculated but do not follow any market mechanisms. They should therefore be seen as indicators, but a real price will come as volumes ramp up.

Infrastructure:

- The state can invest in infrastructure itself or support consumers in purchasing it. It also makes sense to put more pressure on fossil fuels and make them less competitive by pricing in carbon leakage compared to green energies.
- You certainly need your own domestic production, the question is how much that can be and at what costs. In the future, the import of hydrogen will probably play an increasingly important role.
- The question of the amount of hydrogen needed is of course strongly related to the demand for primary energy in the future. However, this is very difficult to estimate.

Partnerships:

- The three legs of the system, production, consumption and distribution, must be built simultaneously and in a coordinated manner. If this coordination is not successful, you have incoherence and then a link in the hydrogen chain is missing.

Interview Notes – Expert 3 (2nd May, 2022):

Introductory Questions – Energy Industry & Complexity:

- The complexity is very high as it is linked to the overarching energy transition. The first step was the transition of mainly primary energy sources and now the question of secondary energy production is on the table.
- Policy makers are trying to connect different stakeholders through a strategic stakeholder dialogue. In addition, a roadmap should provide a way of staying in the valley in this complex landscape and not eventually encountering mountains that are almost impossible to overcome.

Capital Allocation:

- Two to three years ago, things really took off, and in the meantime large corporations are also active through takeovers. But start-ups are now also being founded in the field of electrolysis.
- Large suppliers are currently experiencing supply capacity bottlenecks and have an urgent need to build up additional capacity.

- Through market hedging the German government tries to improve the market conditions and attract additional investments.

Research & Know-how:

- There is still some opportunity for innovation in efficiency. I have a background in the solar cell industry and have seen that scaling and experience curves are the panacea when it comes to becoming economical.
- Just as with wind and solar power, I expect the same scaling effect with hydrogen, because as soon as the market builds up, a kind of momentum develops and through this massive scaling it then becomes significantly cheaper.
- Hydrogen offers the possibility of storing energy as a natural element. The problem is to liquefy hydrogen, as it prefers to take on a gaseous state. In addition, the use of hydrogen on a large scale has only emerged in a useful way recently, as a lot of energy is lost during electrolysis and further processing.

Price Building:

- The demand from the steel or chemical industry, for example, is huge. The only thing missing is that the price is still a little too expensive. But especially if the price of gas becomes more expensive, the demand for hydrogen will increase significantly.
- The CO2 price is a great lever to raise the demand for green hydrogen.

Infrastructure:

- Different regional stakeholders have different orientations. While those in the north of Germany are primarily interested in getting their ports afloat so that they can land hydrogen there, in the south it is more about the users and their needs.
- The infrastructure is crucial because it goes in the direction of security of supply and companies, which are, after all, the demanders of hydrogen, do not like to live with supply bottlenecks.
- The gas infrastructure can be used to some extent for hydrogen, but nevertheless some adjustments are necessary here as well.
- Global dependence can be managed through targeted diversification. Hydrogen also provides the opportunity to do development work.
- I don't think we can produce enough hydrogen in Germany to supply the industries. May guess is that we can serve 30 to 40% of the demand through domestic production.

Partnerships:

- Such declarations of intent are of course also about external impact, to show that something is happening in the hydrogen issue.

Interview Notes – Expert 4 (7th May, 2022):

Introductory Questions – Energy Industry & Complexity:

- Green hydrogen will play a critical role in this energy transition. A number of countries around the world have made some aggressive targets in terms of decarbonisation and in order to come to close to meething those targets hydrogen has to play a critical role.
- Over the last ten years we have seen a quick ramp-up of renewables and they have become mainstream. Renewables only help you in terms of making electricity production sustainable but it is only around 20 percent of the global energy demand. You still have all these other areas that we we call hard-to-abate sectors of the energy mix that demand a transition as well, but the solution is not easy when you have these heavy industrial processes that have been established for such a long time.
- Today the technology is essentially not mature enough and the costs are too high to just go away from our existing way and switch to hydrogen.
- There is now positive momentum where policy makers realise that in order to achieve the targets that we have set, something needs to be done and this process starts with policy measures.

Capital Allocation:

- From a energy transition capital fund, hydrogen aligns with our business model in the longer perspective so we can be patient, but not every investor has the same mandate. Recently, more and more investors are going into this direction but it is still a nascent market, so the number of players that can get their head around the risk given the amount of uncertainty in the market is still fairly low.
- In terms of reaching the inevitable, policy is needed to bridge us to a point where the market can mature and become cost competitive, stand alone.
- As investors we need the optic size of the market to ensure that we see returns and what helps for that is obviously the price, but currently there is still a lot of investors waiting until the price becomes x/$.

Research & Know-how:

- If you believe hydrogen will play a massive role, the scaling part is essentlially what you need to bring cost of electrolysers down.

Price Building:

- Prices are now largely dependent on cost of the primary energy source such as impor cost for energy sources or the intermittency of renewables.
- Currently, it is a bilateral market so it requires more players on the market to increase the commitment. Especially end users are playing a key role in the underlying demand and are maybe willing to pay a premium.

Infrastructure:

- Building on existing physical and mental infrastructure can help to keep the cost down.
- Building infrastructure sits best on the investor side since there is the knowledge, expertise and know-how. The role that policy plays is more economically, so providing tax incentives, fixed quotas and determining location factors to steer the behaviour of energy producers.
- Energy independency has become a crucial issue but still every country will have its limits where they just cannot build more or it becomes too costly again so they have to procure gloablly.

Partnerships:

- At certain project sizes it makes sense to bring in partners due to a capital-risk consideration to ensure make sure we are not overconcentrated.
- Strategic partnerships make sense where we lack know-how and the other can contribute something else. So it is basically about leveraging the strengths of both partners

Interview Notes – Expert 5 (8th May, 2022):

Introductory Questions – Energy Industry & Complexity:

- We currently see the deficits in renewable energy production everywhere and that something has to be done there first. Moreover, it is to be expected that the hydrogen produced will first and foremost go to other industries, but not to the energy industry.
- I would expect a time horizon of 25 years until hydrogen also has an impact on the energy industry.

- It is also crucial that there is intergovernmental coordination on regulation so that there are no disadvantages for businesses.

Capital Allocation:

- Regulatory measures similar to those for renewables must be applied to make the development of hydrogen profitable.

Research & Know-how:

- There is a need for a big capacity expansion, because even though we already see start-ups recognising this issue, it obviously needs a lot of big players.
- There is still a lot of room for manoeuvre in this technology, because there is certainly great potential to reduce costs if electrolysers are produced on a large scale.

Price Building:

- Companies would also like to invest globally, which is why it can also make sense to create market structures in partner countries.
- Hedging of hydrogen trades through government intervention can help to create certainty that production volumes can also be sold in the long term and thus stimulate investments.

Infrastructure:

- From an economic point of view, it is also crucial to know which hydrogen products are needed to build the infrastructure accordingly.
- You can basically produce as much green hydrogen as you need, but of course you need the green electricity to do so, and this is where our limitations lie. Green electricity is already being imported today, but even here there are limitations due to the lack of grids.

Partnerships:

- These cooperations are important because the industry is now facing decisive investments for the next few years. Here, of course, a partner is crucial.
- In the long term, all companies want to be able to buy hydrogen as a commodity from a market with different suppliers, but that will not happen so quickly. Therefore, such partnerships can help in the short-term.

Interview Notes – Expert 6 (8th May, 2022):

Introductory Questions – Energy Industry & Complexity:

- In many countries, national hydrogen strategies are being developed as a result of dialogue with various stakeholders.
- State intervention can, for example, take the form of the development of a taxonomy, steering models in the market, but also fixed purchase quotas. However, the question is also where the limit of state intervention lies. The companies would certainly like to see a fairly market-oriented orientation of these requirements.

Capital Allocation:

- What is currently needed is a great deal of political order, i.e. state intervention in the form of clear guidelines, on the basis of which the companies then have planning and investment security.
- The question is how policy coordination can succeed, because we can see that the energy industry is very complex and hydrogen in particular makes it even more complicated, because this issue goes beyond the energy industry into other heavy industries.

Research & Know-how:

- There are some disadvantages associated with hydrogen: safe storage but also transport, where the question of liquefaction or gasification is a major problem. If we look at other hydrogen derivatives, such as ammonia, the handling here may well be easier.

Price Building:

- In the long term, all companies want to be able to buy hydrogen as a commodity from a market with different suppliers, but that will not happen so quickly.

Infrastructure:

- From an economic point of view, it is also crucial to know which hydrogen products are "- A distinction must be made between pure hydrogen and hydrogen derivatives. These different hydrogen products require different global infrastructures for production or transport, for example, which further increases the complexity.
- Due to the high complexity, there were also problems in politics for a long time to know what kind of infrastructure is needed.

- Renewable energies will cover part of it, but there will still be imports. You can imagine it like concentric circles, where you try to achieve as much as possible on the smallest possible level and then draw ever wider circles, i.e. you open your eyes wider and wider and also turn towards the global South.

Partnerships:

- Through partnerships the capital will be deployed and from there we can build on a market.

Interview Notes – Expert 7 (10th May, 2022):

Introductory Questions – Energy Industry & Complexity:

- In Germany, we used to have an energy system in the electricity sector based on a few central power plants. These provided their energy in a controllable manner and largely in line with demand. A transformation of this system away from the few large conventional power plants to the many decentralised renewable energy producers requires, on the one hand, a massive expansion of the grid because all producers must be connected and, for example, the wind power must be transported from the power generation in the north to the consumption centres in the south and, on the other hand, considerable storage capacities because the renewable energies are only available volatile and can only be controlled to a limited extent.
- However, electricity generation must always correspond to electricity demand in order to be able to keep the grid frequency of 50Hertz stable. This is why energy storage systems such as pumped-storage power plants, battery storage or hydrogen-based storage systems are needed. The latter also offer enormous storage potential for seasonal energy storage. However, energy losses are associated with every type of storage, especially with hydrogen technology.

Capital Allocation:

- In Schleswig-Holstein, there are many projects in the various sectors: Industry, mobility, heat and electricity are being planned. In particular, we see many large-scale industrial projects on the west coast. Therefore, it can be assumed that the demand to invest in hydrogen projects is high.
- The definition of green hydrogen at the EU level is crucial. The current draft of the delegated act will be presented on 18 May 2022. This will contain, among other things, the electricity procurement criteria for green hydrogen. Which electricity may be used for green hydrogen production? Is it possible to purchase electricity from the public grid? Must there be a direct connection to renewable energy generators? How old may these be? Does the electrolysis have

to be located in close proximity? Such questions must finally be clarified in order to create investment security for H2 projects.

Research & Know-how:

- It is generally assumed that the hydrogen production costs will decrease over time and with technological progress. The investment costs for electrolysers have a strong influence. Here it can be assumed that scaling effects and the transition from rather small-scale production with still relatively much manual labour to industrial production will lower the costs for electrolysers. In addition, the technology itself will continue to develop so that, for example, fewer rare and expensive raw materials will be needed in production. Here, for example, the AEM technology is a source of hope. H2 vehicles such as refuse collection vehicles or buses with fuel cell drive systems have so far only been produced in small series and are therefore many times more expensive than conventional vehicles of this type. Here, too, significant cost reductions are possible if large-scale production is introduced.

Price Building:

- The hydrogen economy is still in its nascent stage. There are only very few suppliers of green hydrogen so far. Most projects in SH use their own produced hydrogen themselves or market it via H2 filling stations. Several circumstances are currently influencing the price development of green hydrogen:
- High electricity prices on the stock exchange make an H2 investment less interesting for operators of wind turbines.
- High energy prices for fuels, heating oil and natural gas partly ensure cost parity with green hydrogen, but in the meantime raw material prices, especially for steel, have also risen to such an extent that this has a significant impact on the costs of building a wind turbine and electrolysis.

Factors that can stabilise the price are:

- As many suppliers and demanders as possible in the hydrogen market.
- H2 pipeline infrastructure to be able to market the hydrogen over a larger radius
- A hydrogen trading platform

Infrastructure:

- The development of the infrastructure with a hydrogen pipeline network, electrolysers, H2 filling stations, storage facilities and import terminals, e.g. for green ammonia, is crucial for the development of H2 Economy. Measures can be:
    - Privileging of outdoor electrolysers, similar to the wind industry.
    - Support measures for infrastructure projects
    - Streamlining of approval procedures to save costs and time
- If possible, part of the hydrogen demand should be covered with regionally produced green hydrogen and only the additional demand should be covered by purchases from abroad. Issues such as H2 production costs, transport costs, supply security, local water supply, political stability, etc. must then be weighed up when choosing a location.

Partnerships:

- These bilateral contracts can now be observed at the beginning of the development of a H2 economy. This is of course partly a problem because there are few ways to evaluate and compare hydrogen prices. But the behaviour is understandable, because every producer of green hydrogen needs an assured purchase to refinance his project.

Interview Notes – Expert 8 (11th May, 2022):

Introductory Questions – Energy Industry & Complexity:

- In general, the electricity market will become more decentralised, but the markets will also become more networked in order to be able to generate synergy effects.
- Hydrogen is currently still in the ramp-up phase, on the supply side but also on the demand side.
- I have the feeling that there is now a consensus between politicians and energy producers about the importance of hydrogen. However, the consensus on the scope of the fields of application of hydrogen has not yet been reached.

Capital Allocation:

- My impression is that there is a lot of uncertainty and that many players are still very cautious about spending a lot of money. When it comes to investment projects, however, investors still want a lot of support from politicians, be it for CAPEX or OPEX funding
- The technology is on the threshold of commercialization, which means that the economies of scale and learning effects increase with each additional electrolyser produced. The longer you

wait, the cheaper the investment is expected to be, giving investors an incentive to hold back their investments.

Research & Know-how:

- It is currently the production side that is having problems because there is still a shortage of electrolysers due to the high production costs of hydrogen.
- Of course, in general it is also about the cost degression of renewables, because these largely determine the production costs of green hydrogen. Of course, this question adds to the complexity.

Price Building:

- The electricity sector is the marginal abatement sector in CO2 trading. If there are 100% renewables, so that all CO2 potentials are leveraged, then green hydrogen should be competitive because the CO2 costs of the substitutes, i.e. the fossil fuels, would be so high.
- It is still uncertain what a future hydrogen market will look like. It will be some time before we really have liquid spot market trading as we know it from electricity. Stabilizing the price can be achieved in the short term by storing hydrogen and also by concluding long-term supply contracts.
- Regulatory measures such as the Delegated Act influence the market ramp-up as well as it will for example define simultaneity obligations for the production

Infrastructure:

- Larger amounts of energy can be transported via the existing infrastructure. If you wanted to cover the entire energy requirement with electricity, then the construction of power lines would take on enormous dimensions.
- My idea is that isolated solutions will appear first, with which large industrial centers in particular will be served. The industrial centers will then gradually be networked in order to create synergies. In the last step, there will probably be a transnational infrastructure and the construction of new infrastructure will play a central role.
- Hydrogen trading will not be as widespread as trading in fossil fuels is currently, because there will be fewer countries apart from Japan and countries in Europe that will have a major need for imports.

Partnerships:

- It's about solving the chicken and egg problem because no one wants to invest without having security on the other side. In fact, as far as I know, the perspective is that investors are cautious because they are afraid of ""stranded investments"". These partnerships create mutual dependencies, which can spread the risk.
- The question of infrastructure has been solved for the time being by regulating the relevant grids.

Interview Notes – Expert 9 (16th May, 2022):

Introductory Questions – Energy Industry & Complexity:

- The question of energy transformation is very complex but also not insoluble. The complexity comes from the fact that energy is used in many areas and we also still have great uncertainties.
- Lock-in effects in the energy industry further increase complexity.

Capital Allocation:

- There is a high need for capital and also a high demand. At present, however, large players such as grid operators are still very reluctant to invest a lot of capital unless this is accompanied by high subsidies.
- Besides, regulatory issues also hinder the release of capital. For example, it has not yet been determined what constitutes green hydrogen.

Research & Know-how:

- Infrastructure is a totally relevant prerequisite, because here, too, one can define an optimal design

In the area of innovation and production processes, there is certainly still a need, especially if you look at the efficiency levels. If you also look at how the hydrogen can be transported, i.e. either gasified or liquefied, then there is certainly also cost reduction potential here.

- The higher the volumes that are transported through a pipeline, the lower the costs per unit of energy. Here, the consideration of the entire value chain is certainly also decisive.

Price Building:

- We have the direct cost drivers of hydrogen. About 70% of the costs are currently accounted for by the input energy. Therefore, the expansion of renewables is important for the development of the cost structure. ‘

- When it comes to pricing mechanisms, with hydrogen you also have the market ramp-up, which happens in different phases and will tend to involve bilateral agreements and contracts, especially at the beginning.
- Similar to the natural gas market, bilateral contracts with fixed prices and production volumes can give both sides a certain degree of security. In the transition phase, for example, carbon contracts for difference can provide producers with security of costs and revenues.

Infrastructure:
- The policy will set a strategic framework with concrete guidelines for funding. I find it difficult to say that policymakers are responsible for The infrastructure build-up. Nevertheless, it is certainly the task of policymakers, especially at The beginning when you have this market failure, in the sense of The chicken-and-egg problem, to accompany and subsidise The build up of infrastructure.
- There will certainly be domestic production, but at the same time There will also be a need for hydrogen imports. Even if hydrogen is only used in heavy industry, The production quantities in Germany will certainly not be sufficient. Moreover, The costs in other countries are certainly lower, although There are still uncertainties about transport costs and so on.
- this international component should be considered directly, because The global development of infrastructure certainly requires Even more time.
- It is necessary to create a catalogue of criteria for the development of a global hydrogen economy, in which not only the techno-economic potential but also questions of geopolitical stability should be taken into account.

Partnerships:
- In particular, partnerships of different links in the value chain make sense in order to test the interlocking of different phases in the value chain in a protected legal framework.

Interview Notes – Expert 10 (16th May, 2022):
Introductory Questions – Energy Industry & Complexity:
- Basically, I would say that hydrogen has the potential to change energy production. The question is, of course, how much and in which areas we will see the changes. Theoretically, most areas can be decarbonised through hydrogen.

- In the past, it was thought that blue hydrogen would be used for decarbonisation via steam reforming and CCS. In the meantime, however, the aim is to tackle decarbonisation directly via green hydrogen, which makes the timeline for the ramp-up even tighter.

Capital Allocation:

- Currently, there is still an unclear regulation, for example, of the certification of green hydrogen. Therefore, not many players dare to invest before such fundamental decisions have been made.

Research & Know-how:

- At the moment, the question is how quickly one can achieve breakeven through the conversion of the energy system away from gas and the price explosion of fossil energy sources. This is certainly a positive development for hydrogen as a competitive energy carrier. In this respect, I believe that the direction is clear and that we will not go back also from a geopolitical point of view.
- Even if the price of fossil fuels has risen significantly, there will still be support. Nevertheless, there will have to be subsidies for a long time in order to make it competitive at some point. This is also a bit of a difficulty, because you have to try to make hydrogen attractive as quickly as possible.
- Companies want strong subsidies for OPEX and CAPEX and preferably also exemptions from regulatory requirements.
- If you say that you are mainly going to use green hydrogen, you first have to look at where production should be set up from an economic point of view before the infrastructures are built.

Price Building:

- The baseline is the cost of renewable electricity. In addition, transport is of course also crucial. There will probably not be a classic world market, because the distance of the transport will of course influence the costs in the future.
- The price calculation of hydrogen is very complicated because questions about any offset mechanisms that may exist or, for example, the question of whether transport should take place via pipelines or by ship are also relevant.

Infrastructure:

- Here in Germany, we only have limited quantities of what we can produce ourselves. We will also have to import a lot due to the scarcity of renewables.
- In addition to decarbonisation, the decisions to build a hydrogen economy are certainly also a structural policy issue for many economic regions.
- When we talk about Chile and North Africa, questions of structures on the ground are of course crucial. For example, does one burden the local energy system just to gloss over one's own CO_2 balance? That's why we can't just look at these questions domestically, but must also answer how infrastructures can be created in possible export countries.

Partnerships:

- Hydrogen is a very good vehicle for sector coupling, which means that you can use the hydrogen and the by-products in different places. For this reason, it makes sense to think about this sector coupling in the partnerships.
- Apart from that, it is also related to the investment risk, which is huge and which cannot be thought of as a single company. One is still very dependent.