Beyond Carbon?

Assessing the Carbon Lock-in Risk of Hydrogen Projects in Northern Germany.

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LUCSUS
Lund University Centre for Sustainability Studies

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Abstract:

Hydrogen could play a crucial role in decarbonizing no-regret sectors, such as the steel or chemical industry. It can be produced in different ways, e.g., with renewable energy (green hydrogen) or fossil gas and Carbon Capture and Storage (blue hydrogen). Blue hydrogen could pose a risk of perpetuating fossil fuel dependence. Guided by the carbon lock-in theory, I analyzed the northern German hydrogen economy and the initiative HY-5 with the methods of document content analysis and semi-structured interviews. My findings show a clear risk that blue hydrogen locks in fossil fuels. However, green hydrogen will be an essential puzzle piece in reaching German climate targets. We must be careful not to rely on CCS for longer than intended and not to see hydrogen as the silver bullet. Further research is crucial as the development of hydrogen is accelerating.

Keywords: Hydrogen, CCS, Fossil Fuel Lock-in, Energiewende, Decarbonization, Northern Germany

Word count: 12.000

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Table of Contents

List of Abbreviations

BMBF	Bundesministerium für Bildung und Forschung (Ministry for Education and Research)
BMWK	Bundesministerium für Wirtschaft und Klimaschutz (Ministry for Economics and Climate Protection)
CCfD	Carbon Contracts for Difference
CCU	Carbon Capture and Utilization
CCUS	Carbon Capture, Utilization and Storage
CCS	Carbon Capture and Storage
CMS	Carbon Management Strategy
CO_2	Carbon dioxide
dena	Deutsche Energie-Agentur (German Energy Agency)
EEG	Erneuerbare-Energien-Gesetz (Renweable Energy Sources Act)
EU	European Union
EU ETS	EU Emissions Trading System
FID	Final Investment Decision
H_2	Hydrogen
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPCEI	Important Project of Common European Interest
IRENA	International Renewable Energy Agency
LNG	Liquefied natural gas
NGHS	Northern German Hydrogen Strategy

NGO	Non-governmental organization
NHS	National Hydrogen Strategy
OpEx	Operational expenditures
RQ	Research question
SDG	Sustainable Development Goal
SME	Small- and medium-sized enterprise
TIC	Techno-Institutional Complex

1 Introduction

“Without green hydrogen, we will not achieve our climate targets and the energy transition," says the innovation officer of the German research ministry (BMBF, 2021). Hydrogen could be the 'missing puzzle piece' in transitioning toward climate-neutrality (Heering & Gustafson, 2021). To limit global warming below 2°C, immediate emissions reductions across all sectors are crucial (IPCC, 2023). The need for a fossil-free system is more urgent than ever (Carley & Konisky, 2020). Germany is in a leading hydrogen position worldwide and has high ambitions to pioneer hydrogen technologies and build up 10 GW of electrolyzer capacity by 2030 (BMWK, 2023). The country sees green hydrogen as critical for reaching the climate goals and key for decarbonizing the hard-to-abate sectors, namely heavy industries such as steel, chemical, or long-distance transport (BMBF, 2022a; Cheng & Lee, 2022).

Despite its opportunities, hydrogen should not be regarded as the panacea to solve climate change (Cheng & Lee, 2022). Clean production with zero emissions is only possible with green hydrogen, also called 'renewable hydrogen,' produced by splitting water in electrolysis driven by renewable energy (Cheng & Lee, 2022; Longden et al., 2022). Since green hydrogen is rare, Germany also counts on blue hydrogen as a bridge technology, which is produced with fossil fuels and captures the emissions with Carbon-Capture-Storage (CCS) (Rosenow & Lowes, 2021). The political decision-making on hydrogen is influenced by the broader energy industry and, most of all, by fossil gas. Established companies would benefit from hydrogen expansion (BMBF, 2022b; Machado et al., 2022). Therefore, it is argued that the hydrogen economy could lead to a carbon lock-in (Van de Graaf et al., 2020), meaning to reinforce existing fossil fuel-based systems (Brauers et al., 2021).

This thesis looks specifically at the case of northern Germany and its marketing initiative *HY-5*. The five northern federal states’ economic development organizations – Bremen, Hamburg, Mecklenburg-Western Pomerania, Lower Saxony, and Schleswig-Holstein – present themselves since 2019 as the "green hydrogen alliance," bringing forward hydrogen development and project implementation with the goal of becoming a European leader region (HY-5, n.d.; FS5/HY2). The close cooperation between the five states and HY-5’s status as a prominent network makes this an interesting case. Moreover, they specifically promote green hydrogen and thus potentially serve as an important proponent for the hydrogen economy.

Against this backdrop, my research aim is to find out if hydrogen projects run the risk of a carbon lock-in. I want to identify the relevant actor groups around the hydrogen initiative HY-5 and explore their interests and concerns. Guided by the carbon lock-in theory, I aim to gain insight into the potential carbon lock-in risk in the transition toward hydrogen for this case specifically and for the broader hydrogen landscape. This involves a critical assessment between hydrogen locking in fossil fuels or escaping them through a ‘green’ pathway. Hence, this thesis’ research questions are:

Do hydrogen projects run the risk of locking in fossil fuels in the energy system?
RQ1: Who are the actors around the hydrogen initiative “HY-5”?
RQ2: What are the key actors’ interests, underlying intentions, and concerns?
RQ3: How does this setup contribute to a carbon lock-in?

2 Background

To better understand the topic, I elaborate on hydrogen and contextualize the case in the *Energiewende*. Then, I connect my research to its relevance to sustainability science.

2.1 Hydrogen’s New Role

“The hydrogen’s hour has finally come” (Machado et al., 2022, p. 93): National hydrogen strategies and reports are accumulating worldwide; politicians and energy and industrial sectors are in strong support of hydrogen (Longden et al., 2022). As a fossil-free energy carrier, green hydrogen could become a global enabler for the economy’s decarbonization to net zero (Longden et al., 2022). It fills a crucial gap in the no-regret sectors, where energy electrification processes are not feasible (IEA, 2019). Research shows that steelmaking without emissions is possible with hydrogen produced from renewable energy electrolysis – but at the highest cost (Choi & Kang, 2023; Vogl et al., 2018). However, most hydrogen is still produced carbon-intensively (Cheng & Lee, 2022). While some only favor green hydrogen, many view blue hydrogen as essential for the transition. Both can be used in the same ways, but as the latter still relies on fossil fuels (see Table 1) this has become politically disputed (Heering & Gustafson, 2021). Depending on how hydrogen is produced, its carbon emissions and environmental impact vary substantially (Cheng & Lee, 2022).

Table 1. The Most Relevant Hydrogen Colors.

Note. The GHG footprint is adapted from GEI. This only gives general guidance. Data from Global Energy Infrastructure (GEI), 2021.

Terminology	Technology	Electricity source	GHG footprint
Green Hydrogen	Electrolysis	Wind, solar, hydro, geothermal, tidal	Minimal
Blue Hydrogen	Natural gas reforming or gasification, CC(U)S	Natural gas, coal	Low
Gray Hydrogen	Gasification	Natural gas	Medium, compared to production with coal

Large amounts of renewable energy will be needed for green hydrogen to decarbonize the industry. Along with the transition come many uncertainties, such as energy and hydrogen availabilities, speed of transition, and import and export countries (Longden et al., 2022). The International Energy Agency (IEA) predicts that in 2070, up to 40% of hydrogen will be produced with CCS (IEA, 2020). In contrast, the International Renewable Energy Agency (*IRENA)* believes in blue hydrogen as a transition technology and not more (IRENA, 2020). Machado et al. (2022) urge for more regulations while "hydrogen is becoming mainstream as regards [to] technology and investment" (p. 85). So far, the EU regards hydrogen rather as an addition to fossil gas (Asna Ashari et al., 2023). While it is technically possible to integrate hydrogen into gas pipelines, pipelines solely for hydrogen are also planned (Machado et al., 2022). With more than $70 billion in global public funding, projections show prompt increases in hydrogen production (Hjeij et al., 2022). Nonetheless, some warn of a carbon lock-in with CCS if demand cannot be met with green hydrogen (Belova et al., 2023; Ueckerdt et al., 2021). Lock-ins impede the shift to new, sustainable technologies with their established path, but they can also provide stability against uncertainties due to the many scattered renewable energies. However, the flexibility in renewable energies is needed for zero emissions (Eitan & Hekkert, 2023).

Previous research (Cheng & Lee, 2022; Hekkert et al., 2005; Longden et al., 2022; Van de Graaf et al., 2020) and a commentary (Rosenow & Lowes, 2021) have stated that hydrogen produced with CCS can lead to carbon a lock-in. However, to my knowledge, hydrogen as a 'colorless' technology has never been assessed based on a carbon lock-in theory and evaluated against the potential of green hydrogen – not to mention in Germany. Studies found that the emissions and monetary costs could be substantial for blue hydrogen, leading to the risk of stranded assets (see theory) (Longden et al., 2022). For gas/LNG, on the other hand, Brauers et al. (2021) have identified a highly overlooked lock-in risk in Germany. Buschmann & Oels (2019) found discursive lock-in aspects in the German energy transition in general. Carbon lock-ins in northern German cases have not yet been researched, and the focus on the Energiewende overall is national (Watanabe, 2023).

2.2 Germany's Energiewende and the Case

Germany's energy transition (*Energiewende*) was often seen as a global role model. However, this is increasingly debated as the country is still dependent on fossil fuels and the biggest CO_2 emitter in the EU (Buschmann & Oels, 2019; GASSCO & dena, 2023; Wiertz et al., 2023). The government's climate targets are a 65% reduction in emissions by 2030 (baseline 1990) and greenhouse gas neutrality by 2045 (Bundesregierung, 2021). Contradictory, it recently supported three new LNG terminals (Brauers et al., 2021).

Germany now focuses on building a hydrogen economy. In 2019, the National Hydrogen Strategy (NHS) was announced, even before the EU-wide strategy (Bundesregierung, 2020; Heering & Gustafson, 2021; Sadat-Razavi et al., 2024). To cover the estimated demand of 412 TWh by 2045 and reduce the price, Germany plans large hydrogen imports and electrolysis for domestic production for usage across sectors (Asna Ashari et al., 2023; Schöb et al., 2023). The Norwegian state-owned gas distribution company GASSCO and the German Energy Agency dena issued a feasibility report on the cross-country hydrogen cooperation. It states that Germany's expected demand and needed storage in 2030 would be higher than possible imports from Norway (GASSCO & dena, 2023). By 2030, the updated NHS expects imports between 50-70% (BMWK, 2023). An additional import strategy was planned for the end of 2023 (GASSCO & dena, 2023), but has not been published yet. The NHS does not exclude the import of blue hydrogen and thus remains open to using fossil fuels (Heering & Gustafson, 2021). Today, the German industry and refineries rely on gray hydrogen, which could be a barrier to green hydrogen infrastructure (Asna Ashari et al., 2023; Machado et al., 2022). Researchers criticize that "climate protection is no longer the clearly dominant goal of the energy transition" in Germany (Wiertz et al., 2023, p. 7).

While the share of renewable energy increases, a carbon lock-in prevails (Buschmann & Oels, 2019). Northern Germany has a unique role in the Energiewende as the transition took off with wind energy in Schleswig-Holstein (Watanabe, 2023), and most renewables are located at the coasts of the northern states (Bartels et al., 2022). Similar developments are expected for the future: More than two-thirds of hydrogen production are planned at the coasts (Lux et al., 2022). The Northern German

Hydrogen Strategy (NGHS) is a collaboration of the five northern federal states (NGHS, 2019). It sees 18 hydrogen hubs – where hydrogen is produced, distributed, and used in one place – as launch pads for the regional ramp-up (see Figure 1).

Figure 1. Hydrogen Hubs in Northern Germany.
Note. Adapted from NGHS, 2019.

While a variety of hydrogen networks have emerged (Asna Ashari et al., 2023), this thesis deals specifically with the case of the green hydrogen initiative HY-5 and the Important Projects of Common European Interest (IPCEI) that it promotes (see Figure 2) (HY-5). HY-5 is based on the NGHS and the "brand for international markets" (FS3). It markets the region as favorable for green hydrogen for the following reasons: First, it produces more renewable energy than it uses. Second, the flat lowlands with existing cavern infrastructure enable intermediate hydrogen storage. Electrolyzers for green hydrogen production are already in place or planned. Further, the industry would profit from the infrastructure's "best conditions": All federal states command a port, terminals, and connection to gas grids. HY-5 lastly mentions expertise in renewables and a "strong political will" in the region (HY-5, n.d.). The points indicate the critical relationship between industry and politics. The federal state's development organizations equally finance HY-5's activities; however, one interviewee remarks it would benefit long-term success if companies invested in it. The interviewee emphasized that the states' amounts are relatively low for their considerable results (FS5/HY2).

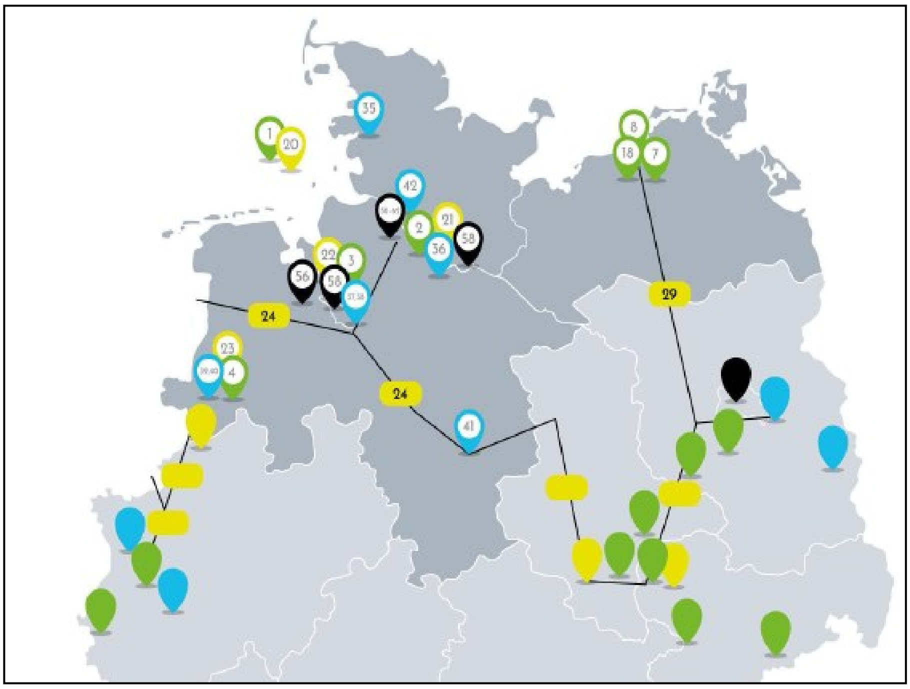

Figure 2. Northern German IPCEI Projects.

Note. Green indicates production, yellow infrastructure, turquoise industry use, and black mobility use. The black lines are pipelines. From HY-5, n.d.

2.3 Relevance for Sustainability Science

A near-term decarbonization of energy systems is needed to limit global warming and lower associated risks (Lantushenko & Schellhorn, 2023). As previously mentioned, hydrogen could play an essential role in this shift. The global transition from fossil fuel dependence to renewable energy technologies addresses several Sustainable Development Goals, e.g., affordable and clean energy (SDG 7), resilient infrastructure (SDG 9), sustainable production (SDG 12), and climate action (SDG 13) (UN, 2015). According to Seto et al. (2016), bringing together these goals requires new thinking about the technologies and institutions relied on for economic growth and perpetuating the status quo. Hence, we must find ways out of the carbon lock-in to maintain climate systems. This thesis contributes to the lock-in literature and sustainability science in exploring the risks of perpetuating fossil fuels dependance through hydrogen, a technology that could also significantly lower emissions in northern Germany to ultimately mitigate climate change.

3 Theory: Carbon Lock-in

The concept of carbon lock-ins guides this thesis as the theoretical framework. I mainly draw on the work of Unruh (2000) and Seto et al. (2016).

Over the last 20 years, research on carbon lock-ins has increased significantly (Buschmann & Oels, 2019; Goldstein et al., 2023). Unruh (2000) defined the concept in his article "Understanding Carbon Lock-In". He describes carbon lock-ins as economies locked in fossil fuel energy systems due to a co-evolution of technological and institutional path-dependencies reinforcing carbon-based systems (Unruh, 2000). This interlinkage of "systematic forces" (Unruh, 2000, p. 817) is called a *Techno-Institutional Complex (TIC)*. Behind that lie networks, institutional actors, and society as a whole that consequently are impeded from changing to – and thus locking out – non-fossil fuel alternative technologies: "Carbon lock-in generally constrains technological, economic, political, and social efforts to reduce carbon emissions" (Seto et al., 2016, p. 427).

The path-dependent patterns that are "self-reinforcing positive feedback" (Krasner, 1988, p. 83) hinder a carbon lock-in escape to other paths that would be following the climate goals (Unruh, 2000). According to the political scientist Pierson (2000), this is reinforced by politics with the intention to uphold the status quo. In fact, many climate-relevant laws favor carbon-intense pathways (Unruh, 2000). Therefore, the best technology for the climate and the people does not always become the *dominant design* (standard technology) and may be perceived as too risky. Not switching to an alternative design despite its apparent advantages is also called *excess inertia* (Unruh, 2000). The government plays a vital role in carbon lock-ins. It has the power to intensify the TIC and can introduce policies that overrule the market. Furthermore, the government usually sticks to what it initially decided, minimizing the chances of introducing technologies at a later point (Krasner, 1988; Unruh, 2000). Formal reasons, such as national security, can easily justify the continuity of carbon technologies and their detrimental consequences (Unruh, 2000). Therefore, "the key question is no longer concerned with understanding the emergence of new technologies but understanding the inertia of a system – a lock-in" (Brauers et al., 2021, p. 3).

There is substantial literature on carbon lock-in conceptualization and assessment (Bjørnåvold & Van Passel, 2017; Buschmann & Oels, 2019; Cairns, 2014; Fisch-Romito et al., 2021; Goldstein et al., 2023; Trencher et al., 2020; Unruh, 2000, 2002). However, Seto et al.'s (2016) work, synthesizing lock-in types and causes, has shown to be the most relevant for researchers (see Web of Science) and is therefore applied in this thesis. They identified three types of lock-ins, namely infrastructural and technological, institutional, and behavioral lock-in effects that are all interrelated. Buschmann & Oels's (2019) research is based on Seto et al. (2016) but found a fourth mechanism, the discursive lock-in, in arguing that discourses justify the very existence of the other types. This thesis considers the infrastructural-technological and the institutional mechanisms relevant to the analyzed case. I exclude the behavioral lock-in as hydrogen is not publicly used (yet); therefore, I could examine behaviors and consumer habits (Seto et al., 2016; Unruh, 2000) only to a small extent, and space is limited. Some aspects, like networks of relationships, are also included in the institutional lock-in (Seto et al., 2016). To correctly identify a discursive lock-in, the additional method of discourse analysis is essential, which goes beyond this thesis' scope.

3.1 Infrastructural and Technological Lock-in

The infrastructural lock-in describes path-dependencies of either infrastructure that directly emits CO_2 in the atmosphere or the so-called supporting infrastructure (e.g., pipelines), indirectly emitting through fossil fuel dependence, and the built physical infrastructure (Seto et al., 2016). Initial decisions and infrastructure investments often imply long lead times, making later changes complicated and expensive. Long lead times also make stranded assets more likely, resulting from the unplanned retirement of a technology scheduled to pay off over a longer time. Decisions on sticking to a dominant technology are always made in the social and political context. However, this does not necessarily contribute to society but might only serve individuals' interests, coined as a "commons dilemma" (Seto et al., 2016, p. 428) - leading to the question of who are the actors benefitting from the status quo. Networks between industry actors, infrastructures, and users evoke network externalities, with effects that reinforce their path and the technological lock-in (Pierson, 2000; Unruh, 2000). Exemplary effects could be new technology standards from industry that reinforce the dominant technology or private financing mechanisms (Unruh, 2000). Following that, economic aspects are decisive for technology choice: The environmentally friendlier alternative is usually not as profitable at that point (Seto et al., 2016). In the past, however, renewable technologies have been shown to become more economically viable over time, while fossil fuels are unlikely to become cheaper (Longden et al., 2022). Favoring carbon nonetheless can be explained by the commons dilemma. Another factor is asset specificity, referring to unique infrastructure that can only be used by the established fossil fuel-based choice. Alternative technologies can, however, also be locked out by other low-carbon technologies (Seto et al., 2016). A special role in the infrastructural lock-in discussion plays CCS as an elementary part of blue hydrogen (Seto et al., 2016), which I will return to.

3.2 Institutional Lock-in

In most cases, institutional lock-ins are intentional by those in power: Actors from the economy, society, or politics who strongly benefit from the status quo. The institutional design reinforces the infrastructural and technological lock-in and thereby causes a fossil fuel lock-in (Seto et al., 2016). Therefore, technological systems are embedded in networks (Corvellec et al., 2013). Powerful actors can follow their interests, whether resisting change or changing it to strengthen their positions further. Policy makers on all scales can benefit from regulatory interventions and upholding the interests of powerful corporations, while they should also function as representatives of society. However, if they fail to represent society, this might result in the end of tenure. In the institutional dimension, the effects of interests take shape in policies, regulations, and inertia to change for the welfare of society and the climate (Brauers et al., 2021, p. 202). The institution interacts with the systemic networks elaborated on in the infrastructural lock-in section (Unruh, 2000), which may result in an energy system favoring fossil fuels that promote the corporations in place.

Once a system is locked in, powerful networks between corporations and political actors are formed, making it more difficult for alternative technologies introduced by 'outsiders' to be chosen (Seto et al., 2016). Unruh (2000) further discusses networks of private associations and institutions influencing society and the market. Generally, it is difficult to escape lock-ins (Seto et al., 2016; Unruh, 2002). However, in the initial stages, alternative climate-friendly pathways can be more easily pursued and achieve long-term goals: "Success in surmounting the challenges of lock-in will be fostered by the involvement and cooperation of actors from different sectors" (Seto et al., 2016, p. 444). In order to be successful, this might need to go beyond the established network dynamics.

3.3 Lock-in Risk for Blue Hydrogen?

Unruh & Carrillo-Hermosilla (2006) already dealt with the implications of CCS and described it as a near-term 'continuity approach'. In other words, this alternative works within the TIC and *continues* the path on the one hand, but, on the other hand, paves the way for a hydrogen economy that could be seen positively. CCS is criticized for still running on fossil fuels, which is why it is of interest to fossil fuel companies (Unruh & Carrillo-Hermosilla, 2006). As blue hydrogen is produced with fossil gas, Van de Graaf et al. (2020) argue that it locks in fossil fuel "trajectories and infrastructure" (p. 2). This shows how long CCS has been debated and underlines the relevance of further exploring the lock-in risk through hydrogen.

4 Methodology

This thesis uses a qualitative mixed-methods approach. I will elaborate on considerations of epistemology and ontology and the research design before discussing the methods.

4.1 Research Design

This thesis underlies a critical realist epistemology and ontology and sees reality and events in the social context needed to make sense of them (Bryman, 2012, p. 29). Therefore, structures of mechanisms must be *critically* identified by social sciences, entailing both observable events and underlying structures. A result of the critical inquiry could be suggesting changes in the status quo, which is very relevant to the carbon lock-in theory (Bryman, 2012, p. 29). A critical glance beyond the merely observable events is needed to uncover the interests, intentions, and concerns that might be connected to the upkeep of the status quo. In using qualitative research methods, I find meaning in how the world is constructed and interpreted (Morgan, 2022) and, more specifically, disclose the underlying interests and not directly observable indicators of a hydrogen carbon lock-in.

4.2 Methods

I combine a qualitative content analysis of public records documents and semi-structured interviews for the mixed methods. The document analysis of official documents in northern Germany helps me gain a general understanding and derive meaning. This method is often used as complementary as a part of triangulation, meaning that the same phenomenon is studied through different methods to reduce biases (Bowen, 2009; Morgan, 2022). Documents can contain contextual, stable, and descriptive data on past and present events, e.g., provide insight into projects and expected runtimes with indicators for lock-ins, which afterwards is interpreted and explored in more depth in interviews (Bowen, 2009; Morgan, 2022). It is, therefore, a deductive approach with the codes and themes based on the lock-in theory, then operationalized and analyzed with the help of the software NVivo (see Table 2) (Bryman, 2012, p. 24). I identified seven official documents by the states' ministries, HY-5 or the NGHS, as relevant for hydrogen developments, with two additional position papers by industry associations to classify the situation. Therefore, I chose nine documents for the content analysis (see Table 3) to answer RQ1 after the involved actors in HY-5 and provide input to RQs 2 and 3. They mainly inform my understanding of the topic and steer the results without being concretely mentioned. I also created an actor mapping, which set the groundwork for the following interviews.

Table 2. Themes and Codes for the Analysis.

Theme	Codes
Infrastructural & technological lock-in	• projects and runtimes • long lead times • economic incentives • asset specificity • network externalities
Institutional lock-in	• institutional design • prior knowledge/experience • actors from politics, federal states • actors from companies, industry • other actors • networks and lobbyism
Decarbonization	• green hydrogen • blue (or other) hydrogen • other energy (carriers) • climate goals

Table 3. Documents for the Content Analysis.

Document (translated titles)	Publisher	Date	Codes
Northern German Hydrogen Strategy	Ministries of the northern German states	November 2019	NGHS
Hydrogen Strategy SH	Ministry for Energy Transition, Agriculture, Environment, Nature and Digitalization	October 2020	SHa
Update of the Hydrogen Strategy SH	Ministry for Energy Transition, Agriculture, Environment, Nature and Digitalization	February 2024	SHb
Hydrogen Strategy State Bremen	Ministry for Economics, Labor and Europe	December 2021 (added August 2022)	HB
HY-5 Green Hydrogen Intitiative of Northern Germany	HY-5	2022	HY-5
Green Hydrogen Hub Europe - Hamburg as a hub for hydrogen imports	Ministry of Economy and Innovation	March 2022	HH
Hydrogen. Energy of the Future in Lower Saxony	Ministry of Economic Affairs, Transport, Housing and Digitalization	March 2023	LS
Position paper on the key points of a Northern German Hydrogen Strategy	IHK Nord - Working Group of North German Chambers of Industry and Commerce	June 2019	IHK
Position paper "Economic growth in the North - Hydrogen, innovation and infrastructure planning"	Unternehmerkuratorium Nord	n.d.	UKM

In semi-structured interviews, the researcher is more active in collecting data to discover the actors' beliefs (Morgan, 2022). In contrast to the content analysis, this approach is more inductive and open to the interviewees' conversations with open-ended questions (Bryman, 2012, p. 12). Some questions were adapted accordingly. The requested interview actors were experts (e.g., from HY-5), political actors, and project partners (mainly companies). I ranked the partners according to the number of involved IPCEI projects and conducted ten interviews between February 29 and April 2, 2024, with representatives of HY-5, the NGHS, politicians, and project partners (see Figure 3). Some stakeholders had overlapping roles identifiable through double codes separated by a /. Half of the interviewees had roles in the federal states, the other half were project partners. Since the interviewees were geographically spread and finding a suitable time slot was easier, the interviews were conducted online (Lobe & Morgan, 2021). Following that, I transcribed the data in Word, translated it, and coded it on NVivo, with the same codes as for the content analysis (Bryman, 2012, p. 13). I analyzed them to answer the question of interests, concerns, and underlying intentions (RQ2) and whether this case might contribute to a carbon lock-in (RQ3).

4.3 Ethics

To ensure research ethics, I obtained informed consent from the interviewees through a consent form (see Appendix D). All interviewees agreed on recording the interviews to enable accurate transcription. The recordings will not be used for any other purposes. I anonymized my interview partners and their organizations and categorized them into actor groups (see Table 4). My research poses no risks to participants.

Table 4. Categorization of Interview Partners.

Categorization of interviewees in actor groups						
Actor group	Federal state actors	Gas operators	Fossil fuel companies	Research institutes	HY-5	NGHS
Description	Actors from the five states' ministries or institutionally linked bodies/staff units	Project partners that operate NG (and H2) pipelines	Project partners whose core business is fossil fuels	Project partners whose expertise is conducting research	Representatives of the HY-5 initiative	Persons involved in the Northern German Hydrogen Strategy
Number of interviews	5	2	1	2	2	3
Codes	FS1; FS2; FS3; FS4; FS5	GO1; GO2	FF1	R1, R2	Overlaps with FS1, FS5	Overlaps with FS2, FS4, FF1

4.4 Limitations

Even though I could balance out the interviewees' categories, reaching the group of project partners was difficult. One company replied that they received too many requests, and another one said they are not involved in the projects anymore (mainly due to regulatory reasons), but many have yet to reply. Overall, the number of interviews is not generalizable for the hydrogen economy in northern Germany, but it gives crucial indications. However, there is still a risk that interviewees reply what they believe is desirable (Bryman, 2012, p. 201). Another limitation is the regional scope of northern Germany since many projects go beyond, and hydrogen imports will lead to global dependencies and relationships. This could be analyzed in further research.

5 Results

In this chapter, I bring together the findings from the document content analysis and the semi-structured interviews to answer the research question of whether hydrogen projects run the risk of locking in fossil fuels in the energy system.

The first section answers RQ1 about the actors involved around the initiative HY-5. This lays the foundation for the other two sub-questions that I address in the sections about the carbon lock-in mechanisms: first, infrastructural and technological lock-in, and second, institutional lock-in. Following that, I include the third coding theme about decarbonization. I regard the challenges and opportunities for the *green* hydrogen economy highly relevant to my research question since it could lock out fossil fuels in the future. However, the more green hydrogen is hindered, the higher the likelihood of using blue hydrogen instead and continuously relying on fossil gas. All quotes in German are translated into English.

5.1 Actor Mapping

I found the actors illustrated below (see Figure 3) relevant in and around the initiative HY-5 through the literature review and the document analysis, with adjustments made after the interviews. The scope is within Germany because many interview partners emphasize their regional focus. For clarity, I illustrate overlaps but omit connection arrows between the actors.

In the center of the mapping is HY-5 with its six representatives who also fulfill other functions in their respective federal states, mainly in the investment/development branch of the state. Therefore, HY-5 overlaps with the states' development organizations. In three states, staff units for hydrogen or similar formed: the Hydrogen Economy Office (Geschäftsstelle Wasserstoffwirtschaft) in Bremen, the Lower Saxony Hydrogen Network (Niedersächsisches Wasserstoff-Netzwerk), and the State Coordination Office Hydrogen Economy (Landeskoordinierungsstelle Wasserstoffwirtschaft) in Schleswig-Holstein.

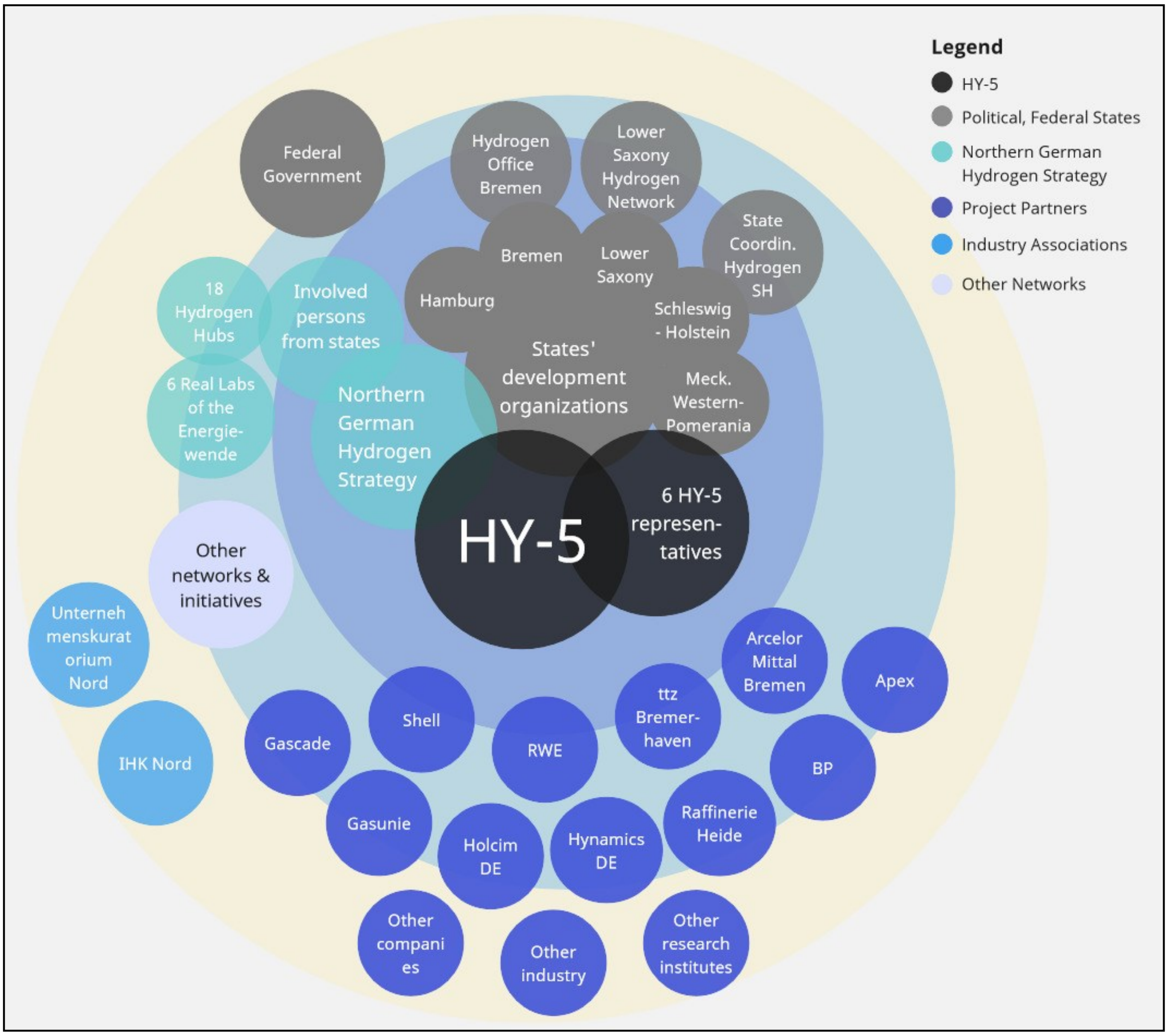

Figure 3. Actors Mapping around Hydrogen Initiative HY-5 in northern Germany.

Note. The blue core includes HY-5 and connected organizations/groups with involved actors. The green circle includes actors with considerable influence – the outer the actors, the lower their connection to HY-5. The yellow circle indicates some importance but not for all federal states.

Some individuals have overlapping functions with the NGHS at the federal state level. The states and HY-5 align with the NGHS (FS5/HY2). Thus, I also placed it in the center. The strategy has five contact persons and more involved persons from the states (and industry) in the so-called working groups. Further, the already mentioned hydrogen hubs and six Real Labs (Reallabore) of the Energiewende are bridging the gap between research and technological application. The interviewees also mentioned other networks and initiatives, but the most significant networks were HY-5 and the NGHS.

HY-5 publicly puts the big IPCEI projects in the foreground that get funding from the European Commission (at the point of the document, 27 in northern Germany). These lighthouse projects for green hydrogen, ranging from pipelines to electrolyzers (see Appendix C), have project partners (HY-5). The partners involved in three projects (Shell, RWE, ttz Bremerhaven, ArcelorMittal Bremen) are placed at the crossover to the center since their decisions might have considerable influence on the region's marketing, bordering with the partners with two IPCEI projects (Gascade, Gasunie, Holcim Deutschland, Hynamics Deutschland, Raffinerie Heide, BP, Apex). The two industry associations, Unternehmerkuratorium Nord (UKN) and IHK Nord, are located in the outer circle between the companies and the NGHS, as they published official statements in that regard. However, I could not identify the extent of their influence. Further portrayed are other companies, other industries, and other research institutes. While these have relevance for one federal state, most are not relevant cross-state. Nonetheless, because of the high number of smaller projects with small and medium-sized enterprises (SMEs), they should be included in the actor mapping for a holistic picture.

Last, I situated the federal government between the federal states and the NGHS, covering both outer circles. As one interviewee put it, there is a "bridge to Berlin from the ministry" (FS4/HS2), but the 'daily business' stays within regional realms. Nonetheless, national politics allocates important funding for the projects and sets the direction for the hydrogen economy. Without it, it would be difficult to justify the northern German efforts (FS4/HS2).

5.2 Infrastructural and Technological Lock-in

In the following, I demonstrate mechanisms indicating the risk of an infrastructural and technological carbon lock-in.

5.2.1 Projects, Run, and Lead Times

The hydrogen landscape in northern Germany has numerous ongoing projects, ranging from local, over cross-regional, to international along the whole value chain (see Appendix A). The data show that most of these are or will be supplied with green hydrogen only, speaking against a perpetuated carbon lock-in. This is because only (planned) green projects receive state funding (FS3). Among these are many electrolysis plants and filling stations – hoping to receive funding for more this year (FS1/HY1; FS4/HS1), projects converting hydrogen to synthetic fuels (R1; R2), and the large-scale IPCEI projects. Long lead times as green hydrogen challenges are illustrated in the decarbonization chapter, as long times do not perpetuate carbon lock-ins for renewable energies but rather decelerate a 'lock-out'. Runtimes are not defined by the interviewees, probably as green hydrogen is considered a sustainable technology that might run for a long time. However, electrolyzers only make sense as long as there is enough demand to operate at least 4,000 hours/year (FS1/HY1). If demand *cannot* be met, the alternative of blue hydrogen might come into play. This can contribute to a carbon lock-in (see chapters 5.4, 6). Nontheless, my interview partners were not involved in blue hydrogen projects in northern Germany.

I found successes but high uncertainties for the hydrogen economy. The certainty for the industry to be connected to a pipeline (FS4/HS2) or from large companies to buy hydrogen (FF1; GO2) is crucial. The question of whether industry or infrastructure should be there first is referred to as a "chicken-and-egg problem" (R1; R2; GO1). Still, the H_2 core network is "unexpectedly a pioneer" in Europe (FS3). The order for the 10,000 km network that connects beyond German borders came from the Ministry for Economics and Climate (BMWK) (see Appendix B). It repurposes gas pipelines that are almost 60 years old, true to the motto: "German steel in German soil – it holds" (GO2). According to GO1, their projects are exclusively planned with green hydrogen "to be consciously climate-neutral." However, they would only have a minor influence on what will be imported from, e.g., Norway or Scotland. GO2 also counts on green hydrogen but admitted that, in the end, it would not matter for them. Their hands are tied to some extent: Gas transportation must be maintained as long as needed for security of supply because not enough hydrogen or other renewable alternatives are available (GO2) (after the coal phase-out, a peak in gas is expected (FS3)).

Pipelines are currently emptied of methane as one first step to ensure a reliable hydrogen supply by 2040, and blends of 2-5% hydrogen are planned to feed in the gas grid by 2025. According to FS2/HS1's estimations, grid fees will be very high for the network operators and ultimately for consumers in the first five to ten years due to less availability than the technical possibility. A major infrastructure project like this proves the long-term ambition and the need for hydrogen to pay off the immense invested costs. As blue hydrogen is not explicitly excluded from these plans and a lack of green hydrogen can be expected, a carbon lock-in risk is emerging but can still be contained.

5.2.2 Asset Specificity

Repurposing pipelines and cavern storage (GO1) connects to asset specificity since structures are reused for a green energy carrier. 40% of European cavern storage volumes are in Lower Saxony (LS). The infrastructure is not specific to fossil gases (which is the definition by Seto et al.) but does not exclude them either. Whether green or blue, the 'technology' (i.e., hydrogen) is the same and can be used and researched for the same purposes (R1; FF1), which poses the risk of using blue instead of green hydrogen. Further, the upscale of blue hydrogen leads to asset-specific infrastructure, e.g., a planned pipeline for CO_2 to Norway and offshore storage with CCS (SZ, 2024). While interviewees mention Norway as an important player, this problem is not acknowledged. Nonetheless, I evaluate the lock-in risk for asset specificity for green hydrogen low and see the difficulty in converting the infrastructure to lock *out* the carbon, which is expected to take decades (FS4/HS2). Maintaining technological openness and relying only on hydrogen where it makes the most sense is crucial to avoid unnecessary energy-intensive hydrogen production instead of treating it as a 'holy grail' (FS3; R1).

5.2.3 Economic Incentives

The green hydrogen economy has many funding opportunities, in contrast to blue hydrogen. When the geopolitical situation shifted with the Russian war on Ukraine, the federal government quickly committed to hydrogen and funded the core network with 19.8 billion Euros (FS5/HY2). Green hydrogen has the potential for decarbonizing German industries but involves high costs. However, incentives are declining: The once outstanding national funding program no longer has money, and subsidies are very uncertain (FS1/HY1). The IPCEI projects were approved under state aid law in different waves, with 70% funded by the government and 30% by the federal states (BMWK, 2024a). Still, the findings suggest divided opinions here. GO1 feels "investment security" with the core network and the IPCEI status of two of their projects. At the same time, one can think critically that scarce (EU) resources should be used carefully and not for several large projects at a time. There are still considerable investment gaps, which affect local actors even more (GO1). There is hope for better, capitalizable investment decisions and a new financing model from the BMWK (GO2). Interestingly, a state actor believes the gas network operators are well-positioned and only need the government if difficulties occur (FS2/HS1).

The Hamburg strategy mentioned that funding is set for a set period "to avoid lock-in effects" (HH, p. 14). However, I regard the lock-in risk low since up to this point, state funding is for green hydrogen projects. There is a danger that this will change with recent developments that I will address in the discussion.

5.2.4 Network Externalities

Network externalities reinforce the other mechanisms (Unruh, 2000) and can be positive or negative (Eitan & Hekkert, 2023). Market prices, competition, standards, and regulations are most prominent and interdependent for the hydrogen economy.

Costs for green hydrogen are incredibly high (FS3). It should be electrified where possible because even cost differences of cents in hydrogen can add up to millions (FF1). The price interaction for electricity and water in some regions is complex and must be adjusted for the industry to buy hydrogen on scale (R1; FS1/HY1). Exemplary are different pricing zones and the north-south divide in Germany that could regionally threaten supply security (GO1) – referring to Unruh's (2000) justification by formal reasons. Once price adjustments are accomplished, the hydrogen market will be there (FS1/HY1), but currently, a business case is not given (R1). One interviewee further mentions that calculations count on the H_2 price going down in time, like with renewables in the past (Longden et al., 2022), but so far, the prices have increased (FF1). For example, calculations in the Hamburg strategy expect a cost decrease (see Figure 4). Hamburg further wants to create private investment incentives (HH). These aspects argue against a green hydrogen ramp-up and thus against a respective lock-in. For the hard-to-abate industry, this could imply continued dependence on fossil fuels.

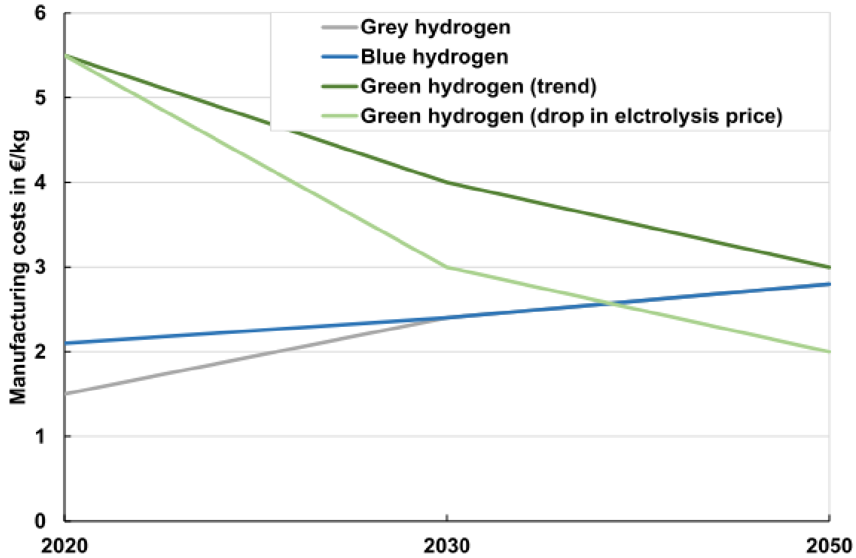

Figure 4. Green, Blue, and Gray Hydrogen Forecasts in Germany.

Note. 2030 assumes a CO_2 price of 100€/t and a constant gas price. 2050 assumes a CO_2 price of 100€/t, a constant gas price, and a carbon import tax of 100€/t CO_2. From Hamburg's Behörde für Wirtschaft und Innovation (BWI), 2022.

Regulations determine whether Germany can keep its industries and companies (FS2/HS1). For example, hydrogen production plants are regulated by the Federal Immission Control Act, making them unnecessarily expensive (FS5/HY2). German industries must compete internationally despite their high costs on many levels. Therefore, it is crucial to leave no one behind and adapt to market developments (FS1/HY1; FS5/HY2). Some studies have excluded the chemical industry in calculations, expecting Germany to import that soon (Schöb et al., 2023). For a fair EU market, FF1 and the Bremen strategy (HB) advocate for Carbon Border Adjustment Mechanisms to prevent carbon leakage. Relevant regulations go far beyond northern Germany, and engaging on the EU level discloses new complexities, with the example of a definition of what counts as 'green hydrogen'.

5.3 Institutional Lock-in

In the following, I identify institutional lock-in aspects and hereby answer RQ2 after the actors' interests, intentions, and concerns.

5.3.1 Institutional Design

"[…] Lock-in is an intended feature of institutional design" to reinforce the status quo of dominant actors (Seto et al., 2016, p. 433). These efforts are rather implicit and show in a hesitancy to change. The interview data suggest that it is difficult to bring about change if politicians are unwilling to promote renewables or the needed infrastructure, urging them to step up and "go down this path together" (R1). Further, it is criticized that politics is still practiced according to the party colors, which is counterproductive for the climate. A "lack of flexibility" of old-established politicians in ministries indicates their contentment with the status quo and may explain insufficient changes (FS3). However, politicians want to keep the industry in Germany and not let them move to more favorable locations for hydrogen (FS3; FS5/HY2). To achieve this, they need to adjust to changes. According to FS4/HS2, companies could adapt to the market and transition if politics introduced more quotas. While I discovered more implications for institutional design under other codes, some interview statements also indicate the opposite of locking in the status quo. Examples are consulting local companies to see whether hydrogen makes sense in their business case (FS1/HY1) or emphasizing the importance of supporting SMEs in the transition (FS3; FS4/HS2). Bremen's strategy points out a specific funding program for SMEs (HB), and Schleswig-Holstein actively wants regional companies to participate (SHa). Further, the ministries are intensely involved in the IPCEI projects for green hydrogen with funding and cooperation (FS2/HS1).

5.3.2 Prior Knowledge and Experiences

Existing knowledge and experiences, primarily from the industry, interconnect the infrastructural and institutional carbon lock-in mechanism by involving established networks and practices.

"One flame you can see, the other you can't" (GO2). The most apparent prior knowledge can be drawn from fossil NG and its existing infrastructure and cooperations (GO2; FS2/HS1; GO1). Fossil gas and hydrogen (and synthetic gas) are very similar, can be phased in pipelines, and can easily be stored in caverns until demanded (in contrast to renewable electricity) (GO2; R2). Gas network operators, therefore, benefit immensely from existing structures and only need to undergo gradual changes to feed in hydrogen. However, they do not exclusively count on green hydrogen since there is a high risk of not receiving sufficient amounts and thus being unprofitable for the next 30 years (FS2/HS1), posing a high lock-in risk in blue hydrogen. My interview partner (GO2) emphasizes that repurposing old pipelines is cheaper, quicker, environmentally friendlier, and publicly more accepted than building new ones, and they plan to repurpose 60-70% of old assets. Particularly, north-west Germany is well-suited to "make use of what we know" regarding hydrogen usage and transportation (FS2/HS1). The industry benefits from the networks and the technology, as it has long used blue hydrogen and ammonia (FS1/HY1; FS2/HS1). Thus, it would not worry about the green hydrogen ramp-up but rather demands a clear outlook to be able to adapt accordingly (FS1/HY1) – if not given, it might also result in a lock-in of blue hydrogen. Only from the researcher's perspective, there would be duplication of work with every new project, mainly due to regulatory adjustments. Research is controlled by strict funding guidelines, and some knowledge gets lost in "squeezing" science into these guidelines (R1).

5.3.3 The Actors' Interests, Intentions, and Concerns

"The energy transition must be promoted and advanced politically" (GO1). Accordingly, it would be up to politics to decide whether hydrogen will become the future technology or not – the market alone would not have enough incentives to change the system as long as it works well for the dominant market players (GO1), linking to the section about institutional design. All interviewees see politicians as significant players in the hydrogen ramp-up that set the direction. One interview partner adds that it is not only the politicians themselves but rather their "invisible substructures [that are] doing the intensive dialogues and big work" (FF1). Referring to RQ2 after the actor's intentions, the data suggest that politics should work with all stakeholders to set goals, define the framework and conditions, and steer implementation across (regional) politics, industry, and research to create affordability of green hydrogen (FS1/HY1; FS3; FS5/HY2). FS4/HS2 concretizes that the federal government sets the tone (which is why it is included in the actor mapping), and the states work with what is given but usually do not 'break out.' Moreover, the hydrogen economy is a global issue, and local efforts are insufficient (FS1/HY1).

Politicians promote green hydrogen and a green economy. Nonetheless, they have also been strongly involved in the LNG terminals' implementation – run on fossil fuels – and felt a "high level of political importance and pressure" (FS2/HS1). While it must be challenging to unite the different needs of society, this is not in line with the energy transition (Brauers et al., 2021). Politicians also demonstrate interest in advancing local hydrogen projects. Even though progress stagnates, politicians must continue their path (FF1). "That's politics" (FF1) is one answer to that – others criticize an inadequate portrayal of the energy mix, leading to exaggerated expectations of hydrogen (GO1; R2) and institutional path-dependencies, as discussed in the theory. In the case of *green* hydrogen, the dependency would not perpetuate a carbon lock-in. If we, however, must rely on blue hydrogen, implications for a lock-in are substantial.

"Transportation is a political business" (GO2). Gas network operators mention a close cooperation and exchange with the BMWK (GO1) and share many insights. Interestingly, the personal place attachment of some politicians is suspected to have been decisive for the hydrogen expansion in some areas (GO2). While GO2 urges for a clear framework and politics without egos, the decarbonization developments could be viewed positively, no matter under which government (with a few exceptions). Gas network operators find themselves in a relaxed situation: "I can sail along a bit. It's nice when others demand what I need" (GO2). For them, it would barely matter if fossil gas did not phase out or if the transition from blue to green hydrogen did not occur, and the efforts ultimately led to a carbon lock-in. By only replacing the gas, the status quo can be maintained for them.

Opinions on the most important actors in the northern German hydrogen economy differ. The gas network operators can be viewed in this role because they must build the core grid first to supply the heavy industry (FS2/HS1). This view is from a political actor, while the gas network operators, in turn, regard politics as the driver (GO1, GO2). However, as a second priority, GO1 also names themselves and collaborations with other operators abroad to create synergies. Three interviewees pointed out that the most important players are those who implement green hydrogen (FS1/HY1; FS3; FS4/HS2). This would be the larger industry, mainly steel, and the suppliers (FS3; FS4/HS2; FS5/HY2). The industry would have its own interest in reducing its emissions to stay competitive with the pressure through the climate goals (NGHS). According to FS5/HY2, the industry should be politically prioritized, and after that, professional mobility. The industry would think they are so crucial that their switch would advance the hydrogen economy at once, knowing that green hydrogen is the only possibility to decarbonize (FS4/HS2; FS3).

Interviewees question what industry will still be in Germany and what we consider crucial in the future (FF1; FS2/HS1). It is strongly criticized that the industry needs to invest more in green hydrogen and take the risk of not being profitable in the first years, which must also be recognized politically. There would be many promising projects, but the FID (Final Investment Decision) ultimately requires “entrepreneurial courage” (GO2). This is lacking from oil and gas players: “We'll support it as best as we can […] but we don't invest” (FF1). The management wants to see how a hydrogen project turns out before it invests in more because of uncertainties on the buyer's side (i.e., industry) that cannot make commitments. Still, they “are always totally interested in talking about it” and vice versa – particularly as the steel industry would enjoy political priority in Germany (FF1). While here, FF1 feels pressure to transform, in other parts of the world it is different. The oil and gas industry thinks they will continue to be profitable with their core business for a long time. Other interview partners generally view the fossil companies' public acknowledgment of hydrogen positively (FS1/HY1; FS3; FS4/HS2; FS5/HY2), believing they “are really working hard on it” (FS5/HY2). While it certainly helps to bring the topic to the agenda, only one interviewee is more critical of greenwashing (FS1/HY1), which is the lock-in of conventional oil and gas, perpetuated by international players.

Despite its importance for progress, research is rarely mentioned without asking for it specifically, whereas the politics-industry relations seem to be more entangled and mutually influenceable. Nonetheless, the role of research institutions in further developing technology is recognized to be "incredibly important" (FS5/HY2; FS3), as is their relationship with industry (HB).

5.3.4 Networks, HY-5, and the Northern German Hydrogen Strategy

Both HY-5 and the Northern German Hydrogen Strategy are seen as crucial for hydrogen development (FS3).

HY-5 is an outstanding example of intensive collaboration (FS2/HS1) with flat structures (FS5/HY2). It is very unusual for federal states to work together this closely with a “very open approach” and the belief in such high potential of something (i.e., hydrogen) that everyone can benefit from it (FS5/HY2). HY-5's aim is “to become internationally visible as Northern Germany […] to tell why companies can settle here well” by all five federal states (FS1/HY1). Further, they manage strategic partnerships, e.g., with Norway and Canada, or ‘share’ here established companies: “That is ultimately the symbiosis of politics and business" (FS5/HY2). From an outsider's perspective, dividing the work is also seen very positively, but it seems that everyone still works on their region, and better exchange among each other would provide additional benefits (R1). Besides, the network's development is currently being discussed in the direction of a commercial network, at the demand of industry (FS5/HY2). As HY-5 exclusively promotes green hydrogen (HY-5), there is no carbon lock-in risk; on the contrary, it advances the energy transition.

HY-5 is based on the NGHS (FS5/HY2) or even emerged from it (FS2/HS1). It also emphasizes "the *green* hydrogen economy," eliminating fossil fuel lock-in risk (NGHS). The strategy was a "joint decision by ministers" (FS2/HS1) to harness the momentum and enable collective advocacy toward the federal government, work together on hydrogen issues, and support external visibility (FS1/HY1; FS4/HS2). One researcher states that the NGHS has significantly advanced the economy and science in ways not possible without it (R1). However, it is not a classical strategy paper but more participative, with five action fields involving different stakeholders – which can also mean different interests and political parties (FS4/HS2; FS1/HY1). Interregional networking and trusting cooperation have emerged from it (FS2/HS1; FS4/HS2; FF1), and FF1 and GO2 were also involved in the working groups. The results of these beyond collaboration are questioned, however (FF1), which may partly be explained by high administration (FS3/HS2) and limited leverage of small players/companies (FF1). FS2/HS1 mentions the complication of the 'double role', namely to act as the NGHS and as a state representative, perhaps using the same logo, and is aware of everyone's individual focus. Yet, discussions are brought forward only with different opinions (FS4/HS2).

Networks, industrial partnerships, and joint projects are exclusively regarded as absolutely essential. All actors must use synergies between economy, industry, research, society, and politics (SHa). Building relationships is a prerequisite for successful project implementation across all levels, with improved cohesion and efficiency over the years (GO1). It can create an understanding of alternative positions (GO2). Without industry participation and funding, networks from the public sector might not be fit for the long term (FS5/HY2) – though it could be discussed whether they still have a raison d'être after the early phases. While networks enhance community cohesion, it is essential that the involved companies also benefit from it (FS4/HS2).

Networks often connect politics with business: Hydrogen project development is "a lot of politics, society, communication partnership with industries, with potential costumers […]" (FF1). The interviewee would typically have connections to large companies regardless (FF1), probably because those who have been part of the dominant system have more resources and influence (Sühlsen & Hisschemöller, 2014). Considering the section on the actors' interests, institutional design lock-ins play out here. Further, there is substantial lobbying for hydrogen to drive favorable decisions, most prominently in Berlin. In northern Germany, smaller networks and clusters are active (FF1). The fossil gas industry also relies on cooperation, as highlighted by the gas network operators. Examples are the core grid consisting of several projects or pipelines, each of which three operators own a third of (GO2; GO1). While the cooperation upholds the current carbon lock-in, a transition to green hydrogen would 'unlock' it and could benefit from existing relationships.

5.4 Decarbonization

The more we depend on blue hydrogen and CCS, the higher the risk of carbon lock-in. Therefore, I want to highlight a selection of findings on blue and green hydrogen and refer back to the committed climate targets.

5.4.1 Blue Hydrogen

Blue hydrogen will be needed to meet near-term hydrogen demand. While Germany has long been critical of CCS, it is now very topical again with a new draft bill (FF1; FS3; FS1/HY1), which I will return to in the discussion. The present shortage of green energy (FS3) explains the current promotion of alternatives but still surprised FS2/HS1. However, introducing *blue* hydrogen to the industry would still bring improvements; the market could develop, and technology and networks could be established (FF1). Particularly with recent electricity price rises, blue hydrogen would be a cheaper, more feasible option than green and still save emissions (compared to gas without CCS).

Since green hydrogen lost momentum, quotas, and regulations against non-renewable hydrogen colors would be "a big mistake" (FF1). FS2/HS1 also speaks out against regulations because Germany will depend on CCS and CCUS during the transition and views blue hydrogen as complementary to green. Another reason is the higher investment risks in the case of insufficient green quantities, which might lead to no more willing investors (FS2/HS1). The interviewees agree that blue hydrogen is needed for the hydrogen economy ramp-up (FS4/HS2; GO2) as long as the focus is on developing the 'colorless' technology (R1). As mentioned in the background, an essential question is *where* Germany will import hydrogen from since it will always be dependent on imports (R1; FS5/HY2). However, the interest behind blue hydrogen is criticized (FS3; FF1) because countries and companies, such as Equinor in Norway, see a business in CCS, and it is no secret they want to use up all their fossil fuels and "still transform it into hydrogen" (FF1). Compared to gray hydrogen, it is evaluated as more climate-friendly if the heavy industry can meet its demand with blue hydrogen from Norway (FS3).

The interview partners point out to be careful to avoid creating new problems with blue hydrogen (FF1; FS3; R1; FS1/HY1; GO2). One big issue with CCS is carbon leakage (FF1): Blue hydrogen could cause more emissions than direct fossil gas usage (Longden et al., 2022). The other obvious risk is that Germany might rely on the 'transitional technology' for much longer than anticipated: "Anyone who says in 15 years' time 'I'm so surprised, blue hydrogen shouldn't be transported in the long term, I'll personally slap them in the face" (GO2), or as FF1 put it: "[…] bridging technology is always such a battle cry or the fear of getting into a lock-in." It is questioned whether there will be enough green hydrogen by 2050 or, ultimately, oil and gas companies will profit from hydrogen produced with fossil gas (FF1). FS3 and FS1/HY1 also emphasized the risk of lock-in effects. To avoid these, only limited time and money should be invested in this technology (FS3).

5.4.2 Green Hydrogen

"There is more hope in it than against it" (FS3).

The more green hydrogen is up and running, the higher the chances of escaping the carbon lock-in. My finding from all interviewees is that green hydrogen will help to decarbonize industries in Germany but it is only "a piece of the puzzle in the energy transition" (GO2). It is crucial to define for what purposes hydrogen makes sense (R1; FF1). Particularly the steel and chemical industries, followed by heavy transportation, are highlighted as the most impactful in possible emissions reductions. In Bremen, e.g., the steel production accounts for ≈50% of emissions (HB). Smaller projects would be equally important in terms of public acceptance, participation, and regional business support (FS4/HS2). Interestingly, the role of hydrogen is estimated as "insignificant" or "subordinate" by the researchers who emphasize the importance of a green energy mix (R1; R2), whereas state actors are most convinced of hydrogen's contribution to the decarbonization (FS1/HY1; FS2/HS1; FS4/HS2; FS5/HY2). Many interview partners agreed that "the first priority is always to use green energy sources" (R1). As previously mentioned, blue hydrogen imports are included on a national level (FS1/HY1), while some northern regions solely support hydrogen from renewables: "Hydrogen from Schleswig-Holstein will be produced exclusively using green electricity" (SHb). Public acceptance would only be high if it is green and has visible social benefits (FS3).

My data show considerable challenges that the green hydrogen ramp-up faces, primarily of regulatory and monetary natures, which must be alleviated to avoid a lock-in through fossil-based blue hydrogen. Consequences are the projects' long lead times. Looking at the IPCEI projects, the "terribly long time[s]" from application to implementation are criticized. It is doubtful whether IPCEI should happen again (FS5/HY2) and if there was an actual benefit (FF1). The target of most projects to be finished by 2026/27 is already unrealistic (FF1). Due to the high funding, the federal states and the EU are strongly involved here (FS2/HS1). Smaller projects take around one-and-a-half years in the planning phase and another one to three years in implementation, but bigger ones take much longer due to the regulatory framework (FS1/HY1). “I’m worried that some timelines can’t be adhered to […] and projects will come to nothing”, one interviewee remarks (FS1/HY1). If current regulations are unattractive, FIDs might be postponed by five years, leading to planning periods of eight years (FS2/HS1). Compared to other projects, hydrogen planning takes much time (FS1/HY1).

Regarding the economic aspects, companies need monetary and operational support as it is challenging to make electrolyzers and green hydrogen profitable (FS1/HY1). Many will want to invest in hydrogen with economic incentives, "but if you can't earn money with green hydrogen, then the ramp-up won't be fast either” (FS3). Support is needed not only during the implementation but also during the operation (OpEx). To some extent, that is being pursued with Carbon Contracts for Difference (CCfD) for the steel, and chemical (HH), industry in closing the cost gap between green and gray hydrogen (FF1). CCfDs are used to support expensive technologies that are essential for decarbonization (BMWK, 2020). The NGHS remarks that “the use of ecologically advantageous products and processes is not rewarded consistently enough” (NGHS, p. 13). A higher CO_2 pricing is suggested to incentivize green energy purchases, best globally (FS2/HS1; FS3; SH; NGHS). An open question is still which company or country would pay for the CO_2 emitted by ships transporting hydrogen – and would it still be *green* hydrogen then (R1)?

The road to hydrogen will undoubtedly be challenging, which is why people need to convince industrial and political actors that it is worth it "to endure this interim pain and not continue to rely on natural gas because it's established" (GO2). It is also acknowledged that hydrogen will create new dependencies, just like every technology that is relied upon – today it is oil and gas (R1). Thus, one should not fully commit to any technology (FF1) because there would not be a single one that is foreseeably sufficient (R2).

All analyzed documents of the five federal states listed their commitment to the climate goals and the Paris Agreement. However, when I asked specifically about its accordance, many interview partners were evasive or unsure. Generally, the targets would "hover over everything," and all efforts would contribute to them, but more implicitly (FS4/HS2). In research, the situation is similar: "The research programs that exist are aligned with these climate targets, but you can imagine a bit of a step-by-step process; we are already a long way away from [them]” (R1). One interviewee criticizes the NGHS, and partly German politics overall, in declaring that strategies are not always or clearly adapted in line with climate goals (FS3): “There is a fundamental lack of a plan as to how we can decarbonize the individual sectors and reduce CO_2 emissions." Concrete measures and a specific reduction target must be defined to reach a goal – currently, it is unclear whether the strategy's goal would contribute to the climate goals (FS3). With no defined decarbonization goals in mind, I evaluate the carbon lock-in risk considerably higher.

6 Discussion

In the following, I discuss the results by linking them to recent developments and scientific literature. Then, I evaluate the risk level of hydrogen carbon lock-ins and make policy recommendations.

6.1 CCS in Germany

The previous chapter highlights the distinction between green and blue hydrogen for reaching the climate targets. As remarked by four of the interviewees (FS1/HY1; FS2/HS1; FS3; FF1), Germany has recently changed its attitude and policy toward CCS/CCU. This is set out in the federal government's key points for a Carbon Management Strategy (CMS) in February 2024: "Without CCS, we cannot possibly achieve the climate targets" (Robert Habeck, Economics Minister) (BMWK, 2024b). The EU also published an Industrial Carbon Management Strategy in the same month.

The hydrogen economy ramp-up to achieve decarbonization is at the forefront of the national key points (BMWK, 2024c). It sets a new institutional frame in politically supporting CCS and the development of corresponding infrastructure, possibly causing increased inertia (Brauers et al., 2021). Critics see a lock-in risk and delayed exit of fossil fuels in these plans (Schwägerl, 2024). While my results show a low risk for asset specificity, the CO_2 pipeline to Norway and other CO_2 pipeline plans (see Figure 5) increase the risk significantly. They are still in the early planning phases, indicating long lead- and runtimes for transporting emissions that we should not emit in the first place. Until completed, the CO_2 will be transported by ship (SZ, 2024), where additional emissions occur (cf. R1). The CMS also mentions that in 2032, it will be decided when between 2035 and 2040 gas power plants will be converted to hydrogen. What I see as very critical is that the emissions trading scheme EU ETS (cf. FF1) is waived for CCS regardless of the transport; this means that the allowance surrender will cease. The same applies to CCU for a permanent CO_2 binding (BMWK, 2024c). This is favorable for companies, as they save money or could even use their purchased emissions allowances for other activities. It becomes clear that the new policies could accelerate the lock-in risk many times. The CMS further states that the potential H_2 core grid operators – of whom I interviewed two – would also be interested in the CO_2 pipeline network (BMWK, 2024c). My interview partners, however, pledged that their efforts would only go into hydrogen pipelines (GO1; GO2).

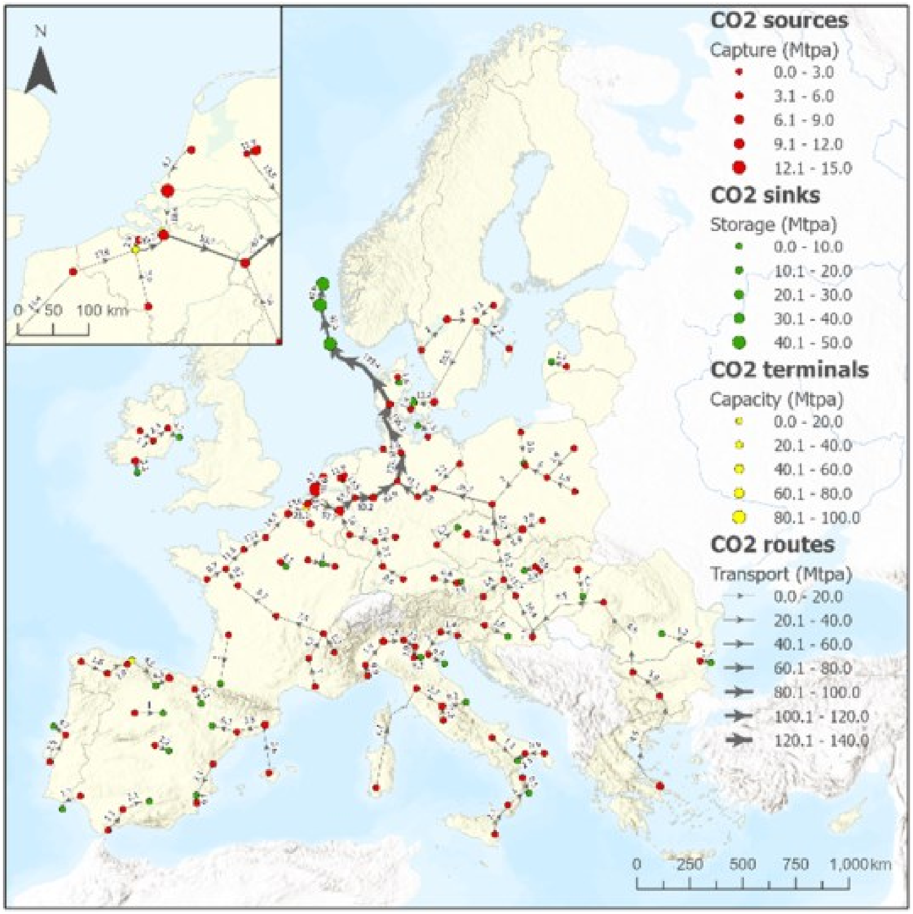

Figure 5. CO_2 Network Scenario for 2050 in the EU, Norway, and UK.
Note. Assumption of approximately 4 Gt of storage. From Joint Research Centre, 2024.

The CMS is justified by stating that CCS is needed for sectors "with difficult-to-avoid emissions" (p. 1) and would only subsidize to stay below 1.5°C and achieve climate neutrality by 2045 (BMWK, 2024c). This is noticeable since I received inadequate responses when asking the interviewees about the hydrogen economy's accordance with the climate targets. Suppose emission reduction is the driver for the ramp-up. In that case, measures, mechanisms, and goals must be in place that 1) steer the industry and other key actors, 2) set clear objectives for the future to minimize uncertainties, and 3) assure that the emission targets will be reached. However, this is missing in the CMS points. The NGHS issue is very similar and lacks concrete plans for climate protection (FS3; NGHS). The results indicate a higher likelihood of being locked in blue hydrogen and CCS for much longer than anticipated instead of relying on green hydrogen in the near future. To avoid this, including clear outlooks and targets is even more necessary. In the next section, I discuss whether hydrogen entails more risk of perpetuating a lock-in or brings more potential to "escape from carbon lock-in” (Unruh, 2002, p. 321).

6.2 Carbon Lock-in or Lock-out?

To answer RQ3 and my overarching research question of whether hydrogen projects run the risk of locking in fossil fuels in the energy system, I further contextualize and interpret my findings.

The data contribute to a better understanding of the complexities in the northern German hydrogen economy around HY-5 that extend far beyond the regional scope. Many challenges have been a concern for projects throughout the EU. Still, with its high ambition to become a green hydrogen economy pioneer and favorable local conditions, northern Germany demonstrates lower carbon lock-in risks than other regions. The interviews show that many professionals within this field are passionate and have high hopes for hydrogen and its decarbonization potential, the great majority specifically in green hydrogen. However, all interviewees also see difficulties in varying degrees. These include the high costs along the whole value chain, insufficient renewable energy for electrolysis, insufficient hydrogen to meet demand, and high future uncertainties. Further mentioned are new dependencies, regulatory and funding complications and thus long lead times, a lack of climate targets integration, unclear priorities in terms of applicability, and last but not least, a lack of courage to take risks for all actors.

The interviewees agree that blue hydrogen is needed in the beginning for the ramp-up, where I see parallels with the already-mentioned feasibility report: “[…] the purchase of low-carbon hydrogen is expected to be necessary and therefore desirable” (GASSCO & dena, 2023, p. 2). I find it questionable to equate necessity and desirability. While some interviewees see a complementary development of blue and green hydrogen without risks, others worry about a carbon lock-in through blue hydrogen. My evaluation of lock-in risk for this case is portrayed below in single aspects (see Table 5), but I want to emphasize that they are mutually reinforcing.

Table 5. Final Evaluation of Lock-in Aspects and Mechanisms.

Lock-in Aspect	**Findings**	**Summary Mechanism**
Projects, Run and Lead Times	• **Long lead times** (depending on project size), undefined runtimes, **variety of projects** *but* mostly for green hydrogen • Still, a lot of invested time and resources	***Infrastructural and Technological Lock-in*** • Relatively high lock-in potential due to high green hydrogen costs and many investments despite uncertainties.
Asset Specificity	• Discussed in Chapter 6.1 • **Lock-in risk for hydrogen is high** due to major infrastructure plans (pipelines) • Carbon lock-in risk **high with CCS** specifics	
Economic Incentives	• **Many incentives for green hydrogen**, could still be improved and during OpEx • Now also **incentives for CCS/CCU** (blue) • Future uncertainties, lock-in risk fairly high	
Network Externalities	• Increase of lock-in potential to keep companies in region, be **profitable against competition** • Many **regulations to promote green H2** to be increased (on EU level as well)	
Institutional Design	• Points speaking for and against uphold of status quo and carbon lock-in → **ambivalent**	***Institutional Lock-in*** • Lock-in risk is certainly there but many networks try to steer it in a sustainable direction with future. However, political struggle with networks promoting fossil fuels
Prior Knowledge and Experiences	• Considerable existing networks, infrastructural and technological knowledge to make use of • **Could be used for or against the transition** → either support green ramp-up or lead to continued fossil gas due to proitability	
Actors' interests, intentions, concerns	• **Political support** is stable but wished for more • Pride, projects are pulled through regardless • **Financial interests** a decicive factor • Hope for decarbonization is present • **Opportunities but risk to stick to fossil fuels**	
Networks	• **HY-5 and the NGHS viewed positively** for energy transition with more potential than risks • Depending on cooperation/lobbying focus → results show overall lower carbon lock-in risk	

The results fit the theory of carbon lock-ins by Seto et al. (2016) and Unruh (2000) to a large extent. Seto et al. also distinguish between carbon lock-ins as bad and lock-ins as neutral, which is emerging here. Yet, the theory must consider the possibility of sustainable *and* fossil-fuel pathways starting within the same technology. While a lock-in in green hydrogen would not contribute to carbon, it is still a lock-in situation. I agree with Goldstein et al. (2023): “The literature typically frames lock-in as negative and intractable, however […] not all lock-in is negative for all” (p. 12). This complicates answering my research question, as it is a balancing act between the advantages and potentials of green hydrogen and the disadvantages and risks of other hydrogen 'colors'. Further, all energy technologies have positive and negative aspects, even if they escape the carbon lock-in. Acknowledging this balance could make the theory more applicable to new challenges emerging during the energy transition. I must note that I look specifically at the CO_2 emissions and their lock-in risk. I am aware that non-fossil hydrogen also poses other problems that go beyond this thesis' scope.

Previous research has also advocated for more regulatory stringency in hydrogen strategies, fossil-fuel penalties, and exclusive support for renewable hydrogen (Cheng & Lee, 2022). This is in line with my findings. However, Germany is placed in the 'medium stringency group,' which may be assessed differently now. Further research has shown that the stronger the networks, the harder it is to overcome lock-ins (Brauers, 2022). My thesis demonstrates that strong ‘green’ networks, like HY-5, can also have the opposite effect. This is in agreement with Machado et al. (2022) and Rosenow & Lowes (2021). They have found it crucial which color of hydrogen dominates. “Blue hydrogen is best viewed as a distraction […]," but green hydrogen could advance decarbonization (Howarth & Jacobson, 2021, p. 1685).

My findings confirm the risk of a hydrogen carbon lock-in. As Germany publicly supports blue hydrogen with no concrete plan of when and how to switch, and green hydrogen is no business case in the near future, the chances are high that blue hydrogen will emerge as the dominant technology. A worst-case-scenario would be not having enough storage or transport capacities for the CO_2, and thus having to use gray hydrogen. This is environmentally devastating, even in comparison to gas as a direct energy source (due to hydrogen’s inefficiency) (GASSCO & dena, 2023). This could significantly delay a net-zero energy system (Brauers et al., 2021). However, I want to emphasize the term *risk,* meaning it could still be avoided theoretically. The usage of any other than green hydrogen must not be framed as sustainable to make all actors actively aware of this risk. According to Seto et al. (2016), “escaping carbon lock-in will require undertaking significant initiatives and investments […]” (p. 427). Green hydrogen proponents and networks are pursuing this.

6.3 Recommendations

Based on my findings, I make policy recommendations that could reduce the risk of a carbon lock-in while supporting the development of green hydrogen. I identified three main themes: policies and regulations, research and applicability, and networks and people (see Table 6). I do not evaluate the realistic feasibility as this would require new methods.

The first category includes establishing clear and favorable framework conditions for green hydrogen projects (FS1/HY1; FS2/HS1; FS3). Further, higher and broader CO_2 pricing (FS2/HS1; FS3) (more) incentive schemes and contracts like CCfDs (cf. FF1) and shorter planning processes would be beneficial. Further introduced in the whole economy should be a minimum CCS capture rate and a maximum methane leakage rate, a lifecycle emissions assessment, and independent monitoring mechanisms (Renewable Hydrogen Coalition et al., 2024). The key actors here are politicians. It is also crucial for political actors to revise hydrogen strategies according to the climate targets and, thereupon, set emissions goals (FS3). This could happen under consultation from independent researchers, leading to the second theme. Researchers must identify where hydrogen makes the most sense in the near future and prioritize accordingly due to the exceeding demand (R1; FF1). This requires cooperation from all other actors. Additionally, the state should be more open toward research needs so that meaningful research can be carried out without too many compromises due to tight guidelines (R1). Hydrogen should be incorporated in education and industry-academia collaboration must be strengthened (NGHS; Asna Ashari et al., 2023).

In the third category, interaction and networking should continuously be improved for more exchange and synergies (R1; FS4/HY2). This also applies, but not only, to HY-5 and the NGHS. The NGHS could benefit from measuring its success or interim goals (FS3; FF1). Strengthening cooperation across federal states and countries (FS2/HS1; GO1; GO2; Van de Graaf et al., 2020) is another recommendation, though already pursued. Lastly, convincing people of the potential long-term benefits of hydrogen (GO2) is essential. Storytellers can come from politics, media, and industry. Connected to that, I identify the need for a distinctive framing between hydrogen forms and colors, increased awareness of the risks that blue hydrogen entails, and the need to make hydrogen visible to society (FS4/HS2; Buschmann & Oels, 2019). The discourse around this could be further explored in new research.

Table 6. (Policy) Recommendations for Hydrogen.

Policies and Regulations	Research and Applicability	Networks and People
Clear and green-favorable framwork conditions	Identify most important applicability for hydrogen in the near future and prioritize usage	Improve interaction and networking (among others, in HY-5 and the NGHS)
Revise hydrogen strategies and plans and ensure accordance with climate targets → define emissions goals and measures		Regularly measure success and interim goals of NGHS
Higher, broader (best global) CO2 pricing	More openness for supporting most meaningful research without major compromises	Strengthen cooperation across states and countries
(More) incentive schemes and contracts, e.g., CCfDs	Include hydrogen in universities and other education	'Tell stories' around hydrogen and convince actors to take risks
Shorten the planning process	More acknowledgement of research and industry-academia collaboration	Raise awarness on the lock-in risk and frame blue hydrogen more critically
Minimum CCS rate, maximum methane leakage rate		Make hydrogen visible to the public, e.g., through mobility
Lifecycle emissions assessment, independent monitoring		

7 Conclusion

By analyzing the northern German hydrogen landscape around the green hydrogen initiative HY-5, I have shown that there is a risk of falling into a fossil fuel lock-in through hydrogen projects in this case. However, this thesis has demonstrated that this issue cannot be treated as black-and-white, and the hydrogen economy also uncloses many opportunities. The distinction between H_2 produced from renewables and fossil fuels is crucial for determining a carbon lock-in risk. Therefore, green hydrogen has the potential to decarbonize the hard-to-abate industry but entails more uncertainties. In particular, the high costs, complicated regulations, and low availability are problematic and might lead to increased reliance on blue hydrogen and CCS, which contributes to a lock-in in fossil fuels.

To return to my research aim, I conclude that the carbon lock-in risk is high for the usage of blue hydrogen, while green hydrogen could theoretically unlock us from current fossil fuel dependencies. Both the potential and the difficulty lie in the colors' interchangeability.

This thesis has also shown the need for more connection in the analyzed case between decarbonizing efforts in hydrogen projects and the ultimate goal of achieving our climate targets. Raising awareness and actively integrating them could help escape the carbon lock-in. If the CCS path continues, it could reinforce old structures that benefit the oil and gas industry, hindering decarbonization and reaching the climate targets that Germany and the EU have committed to. This applies to hydrogen projects beyond this case. I have further found that the infrastructural and technological lock-in aspects are stronger than the institutional ones. This is mainly because of very high investments, long project times with more risk, and promising networks and political support for the green alternative. Nonetheless, the recent CCS developments might increase the lock-in risk for both mechanisms. Further recommendations to avoid this concern policies and regulations, research and applicability, and networks and people.

Further research could expand on this thesis and analyze the German situation once the new Carbon Management Strategy is implemented. Will the risk of a carbon lock-in increase? Under which circumstances could a lock-in be good? How can we lock out carbon? Moreover, the (northern German) hydrogen economy could be studied regarding behavioral and discursive lock-in mechanisms as increasing use will offer more observations. Since this thesis focuses on large-scale projects and partners, future studies could take into account small- and medium-sized companies' perspectives, considering the repeatedly mentioned risk of losing German companies. Further, it could be beneficial to study the ambivalent topic from environmental scientists' and NGOs' points of view, especially since the two researchers are less convinced of hydrogen than the other interviewees. Last but not least, I am convinced there will be many new developments and turns concerning hydrogen in the future, opening up much more potential for research.

This thesis demonstrates that we should take the risk of blue hydrogen seriously and carefully revise investments and measures that aim at the respective targets. It shows that critical thinking about actions and actors' intentions, as well as courage for change, are the qualities that the green hydrogen ramp-up needs more of. Nevertheless, in the end, hydrogen is just one part of the energy transition. No technology will save the earth and we must immediately reduce our emissions (IPCC, 2023).

"Right now we're in the middle of a major change. Because one thing is 'switched off' […], the next thing is switched on" (R2) – and we can still choose the right path.

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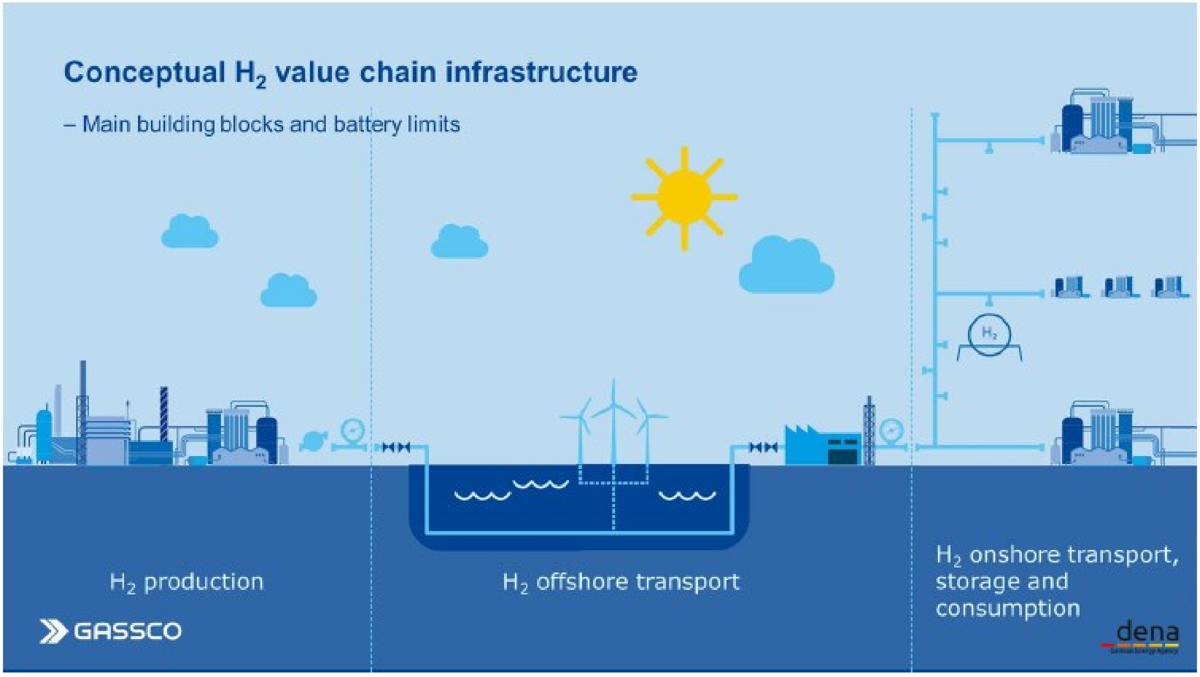
9 Appendix

Appendix A

H_2 Value Chain

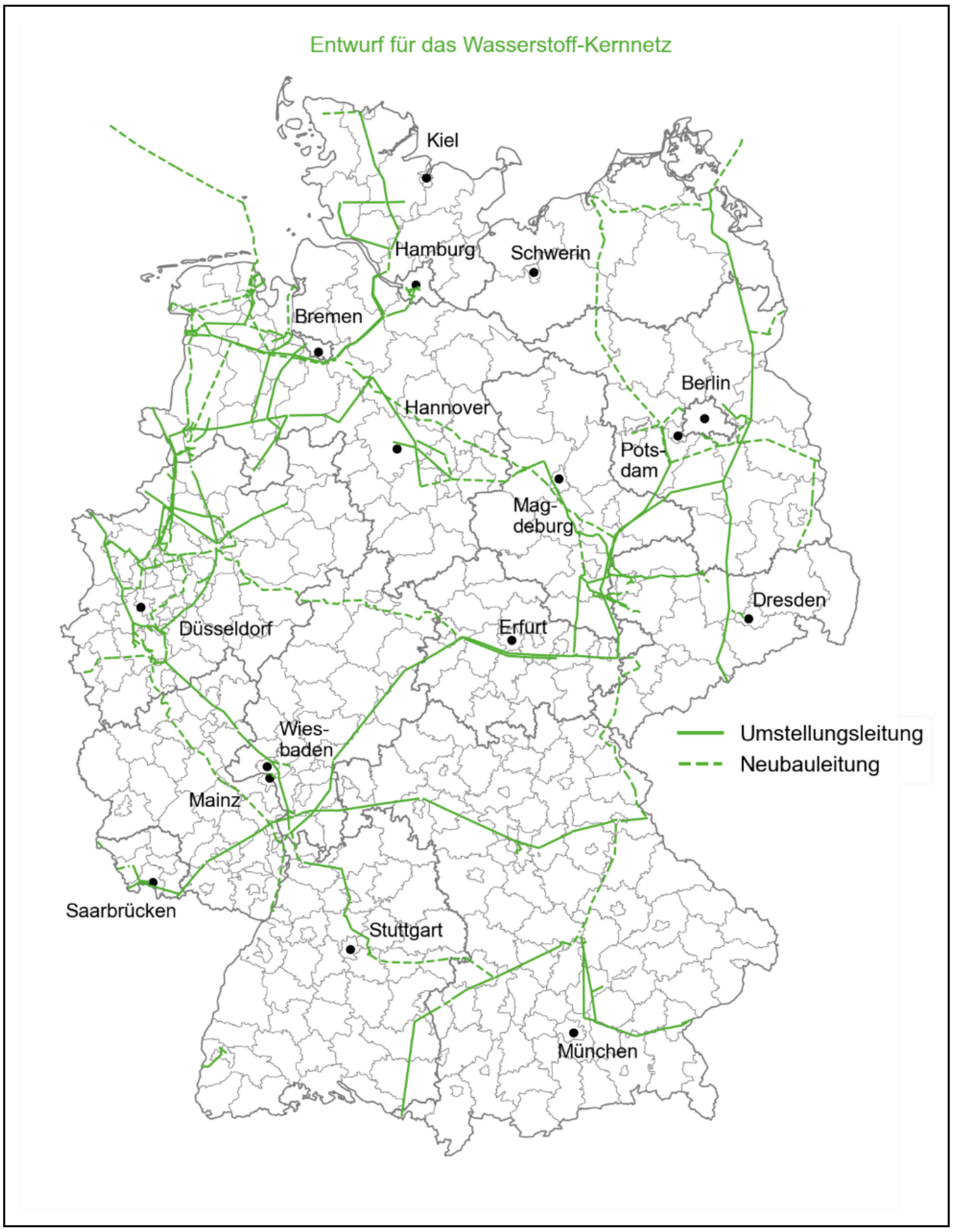
Note. From GASSCO & dena, 2023.



Appendix B

Draft for the Hydrogen Core Network

Note. From FNB Gas, 2023.



Appendix C

IPCEI Projects in Northern Germany.

Note. Data from HY-5, 2022.

Project	Type	Federal State(s)	Partners	Runtime
AquaPrimus 2	Production	Schleswig-Holstein	Shell, Siemens Gamesa, Siemens Energy, RWE u.a.	2021-2025
AquaDuctus	Infrastructure	Schleswig-Holstein	GASCADE, Gasunie, RWE, Shell, Equinor	2035
Rethinking Mobility	Production, Mobility, Usage	Schleswig-Holstein	GP Joule	2009 Foundation
HyPerLink	Infrastructure	Niedersachsen, Bremen, Hamburg, Schleswig-Holstein	Gasunie, Energinet	2021-2025/30
HySCALE100	Production, Industry	Schleswig-Holstein	Holcim Deutschland GmbH, Hynamics Deutschland GmbH, Ørsted Wind Power Germany GmbH, Raffinerie Heide GmbH	2021-2027
WESTKÜSTE 100	Production, Industry	Schleswig-Holstein	Holcim Deutschland GmbH, Hynamics Deutschland GmbH, Ørsted Wind Power Germany GmbH, Raffinerie Heide GmbH	2021-2027
GET H2	Production, Storage, Transport, Industry, Mobility	Niedersachsen, Nordrhein-Westfalen	BP, Evonik, Nowega, OGE, RWE, Salzgitter AG, Thyssengas	2022-2026
Green Crane Lingen	Production, Storage, Transport	Niedersachsen	Enagas, Naturgy, Vopak, Hydrogenious LOHC Technologies	2022-2025
Lingen Green Hydrogen	Production, Industry, Storage	Niedersachsen	BP, Ørsted	2022-2025
First hydrogen train	Mobility	Niedersachsen	ALSTOM. CORADIA iLINT	Since 2020
Green Hydrogen Hub Hamburg	Production, Logistics, Industry, Storage	Hamburg	Shell, Mitsubishi Heavy Industries (MHI), Vattenfall, Wärme Hamburg	2021-2025
HH-WIN	Distribution, Supply, Industry	Hamburg	Gasnetz Hamburg, Wasserstoff-Verbund Hamburg	2021-2030
HHLA H2LOAD	Logistics, Port handling, Heavy cargo transport	Hamburg	HHLA Hamburger Hafen und Logistik AG	2021-2027
Green Gas for Bremerhaven	Production, Alternative fuels, Mobility, Logistics, Food industry	Bremen/ Bremerhaven	Hochschule Bremerhaven, Fraunhofer IWES, ttz Bremerhaven	2020-2030
Clean Hydrogen Coastline	Production, Storage, Steel, Mobility	Bremen, Niedersachsen	EWE, swb, ArcelorMittal Bremen, FAUN, Tennet	2023-2026
DRIBE	Industry, Steel	Bremen	ArcelorMittal Bremen	2023-2026
WIPLiN	Aviation, Industry	Bremen, Hamburg, Niedersachsen	Airbus Operations	2021-2035
The future's power-to-gas-facilities	Production	Mecklenburg-Vorpommern	Apex Group	2002 Foundation
HYTechHafen Rostock	Production, Industry, Storage, Logistics	Mecklenburg-Vorpommern	YARA GmbH & Co. KG, Rostock Port, Wind project IWEN	2022-2030
doing hydrogen	Production, Industry, Storage, Logistics	Mecklenburg-Vorpommern	Gascade Gastransport GmbH, Ontras Gastransport GmbH, Apex Energy Teterow GmbH, Cemex Zement GmbH, Enertrag AG, Geo Exploration Technologies GmbH, Wintershall Dea GmbH	2022-2026
E-Methanol DOW	Production, Industry	Hamburg (Stade)	DOW	
Hydrogen Port Applications (HYPA)	Mobility, Infrastructure	Hamburg	HPA Hamburg Port Authority	2024 Start
H2HADAG	Mobility	Hamburg	HADAG Seetouristik und Fährdienst AG	2022 Start

H2 Push Boat (H2SB)	Mobility, Shipping	Hamburg	GreenPlug: builds and leases ships Eckelmann / Hans Wolkau: Ship operators ILF: Energy system design	2022-2027
DRIBE2 - Direct Reduced Iron Bremen Eisenhüttenstadt	Industry, Steel	Bremen	ArcelorMittal Bremen	2023-2026
Energy Port Bremerhaven	Production, Industry	Bremen/ Bremerhaven	Senatorin für Wirtschaft, Häfen und Transformation, bremenports, BiS, FBG	2023-2026
ITZ Nord - Innovations- und Technologiezentrum Nord für die Luftfahrt und die	Innovation, Aviation, Shipping	Bremen/ Bremerhaven	ttz Bremerhaven, DLR Institut für Raumfahrtsysteme, ITZ Nord e.V.	2023-2026
MariSynFuel - Synthetisches Methanol als maritimer Kraftstoff	Shipping	Bremen/ Bremerhaven	ttz Bremerhaven u.a.	2023-2026
Umrüstung HBB-Rangierlokomotiven auf Wasserstoff-Verbrennungsmotoren	Mobility, Infrastructure	Bremen	Hansebahn Bremen GmbH	2023-2026

Appendix D

Consent Forms for the Interviews.

CONSENT FORM

Theme of Study:	Hydrogen economy in northern Germany
Principal Investigator/ Name of Student	Nastassja Celine Henkel

General Information

The aim of the interview is to get a better understanding of hydrogen projects and developments toward decarbonizing the economy in the case of northern Germany.

This interview will take approximately one hour. Participation is voluntarily and anonymous, meaning that names and any information that would reveal the identity of the participant will not be published nor shared with anyone.

The interview is structured in three blocks. I will guide the discussion in posing the questions and the participant is expected to answer them based on their own expertise and experience. The participant is encouraged to share any further information, thought, or idea freely that comes to their mind.

Compensation

This interview soley contributes to the data collection of a Master's thesis project of Lund University in Sweden. Collected data will only be used for the Master's thesis. There is no financial benefit or compensation for the participation.

Benefits/Risks of the Study

Physical or mental risks are not associated with participating in this study.

Confidentiality

If the participant agrees, the interview will be recorded. The interview recording will not be shared with third parties. The Master's thesis will be published at the website of Lund University Library. The confidentiality and anonymity of interviewees will be maintained, meaning that any interview minutes or data used will not include any personal details of the participation.

Withdrawal from Study

The participation is voluntary, and participants may withdraw at any time without penalty. The participant will not be negatively affected if they decline to participate or withdraw from the study at any point. The participant can freely decide not to answer specific questions if he/she considers sensitive.

Contact for Additional Information

I will be available to respond to questions or any research-related inquiry at:

- Name of Researcher: Nastassja Celine Henkel
- Title: M.Sc. Student in Environmental Studies and Sustainability Science at Lund University
- E-mail: na8237he-s@student.lu.se

PARTICIPANT AGREEMENT

"I have read or have had someone read all of the above-asked questions, received answers regarding participation in this study, and am willing to give consent for me to participate in this study. I will not have waived any of my rights by signing this consent form. Upon signing this consent form, I will receive a copy for my personal records."

____

Name of Participant

____________________________________ __________________

Signature of Participant Date

____

Name of Person who Obtained Consent

____________________________________ __________________

Signature of Person Who Obtained Consent Date