Permanently stored, permanently trapped?

A study on the risk of carbon lock-in through the German-Norwegian partnership in CCS and hydrogen

Lena Faber

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Sustainability Studies

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Abstract:

As the climate crisis becomes more severe, carbon capture and storage (CCS) is increasingly seen as a viable option to help mitigate climate change. However, one risk with regard to CCS is that it locks us into the use of carbon-based energy sources and industry, creating a carbon lock-in. Looking at the German-Norwegian partnership to store German CO2 in Norway and to provide hydrogen in return, this thesis investigates how this partnership creates a carbon lock-in in Germany. The results of the qualitative content analysis and semi-structured interviews show that the CCS partnership and its concrete projects unfold both infrastructural and technological, as well as institutional carbon lock-in mechanisms. Thus, CCS is problematic as it upholds the status quo of fossil-based energy sources and industry, inhibiting real change towards a fossil-free and zero-emission world, while at the same time being promoted as a necessary technology to reach Germany’s climate goals.

Keywords: CCS, carbon lock-in, blue hydrogen, Germany, Norway, climate change mitigation

Word count: 11.872 words

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Thank you, Henner! My favorite amongst your comments in one of my drafts was: “Der Titel ist kacke, weil auch grammatikalisch falsch”. Jokes aside, I valued your honest feedback and I want to thank you for never making me feel like I am too far behind, even in late February when I was still figuring out what to do.

Thank you also Lina and Jonas for your early support in finding a good topic and sending some important readings. I don’t know if you will read this thesis, but if you do, I hope you find it interesting.

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List of abbreviations

AHK	Außenhandelskammer (German Norwegian Chamber of Commerce)
BECCS	Bioenergy with carbon capture and storage
BMWK	Bundesministerium für Wirtschaft und Klimaschutz (Federal Ministry for Economic Affairs and Climate Action)
CCS	Carbon capture and storage
CCU	Carbon capture and use
CCUS	Carbon capture use and storage
CDR	Carbon dioxide removal
CO2	Carbon dioxide
COP	Conference of the parties
DACCS	Direct air capture with carbon capture and storage
DENA	Deutsche Energie Agentur (German Energy Agency)
EOR	Enhanced oil recovery
EU	European Union
GER	Germany
GER-NOR	German-Norwegian
H2	Hydrogen
HDI	Hydrogen Direct Reduction
IPCC	Intergovernmental Panel on Climate Change
KSpG	Kohlendioxid-Speicherungsgesetz (CO2 storage law)
LNG	Liquified natural gas
NCS	Norwegian continental shelf
NOR	Norway

1 Introduction

"Better put CO2 into the ground than into the atmosphere" (Bellona Europe, 2023).

With this sentence, the German Federal Minister for Economic Affairs and Climate Action Robert Habeck justified the new German-Norwegian carbon capture and storage (CCS) deal included in the countries' Partnership on Climate, Renewable Energy, and Green Industry. On 5 January 2023, Germany and Norway issued a Joint Declaration and a Joint Statement, which include plans for Norway to store German CO2 at storage sites in the North Sea, while at the same time, Norway shall send blue hydrogen to Germany, produced with fossil gas and CCS (Office of the Prime Minister & Ministry of Petroleum and Energy, 2023; Office of the Prime Minister & Ministry of Trade, Industry and Fisheries, 2023).

As the global average temperature keeps rising, CCS is often referred to as a necessary technology to reach the 1.5°C target as set out in the Paris Agreement (International Energy Agency, 2021). Furthermore, the Intergovernmental Panel on Climate Change (IPCC) includes CCS as an important option to reduce carbon emissions (IPCC, 2005, 2022). According to the newest IPCC report, "CCS is an option to reduce emissions from large-scale fossil-based energy and industry sources" (IPCC, 2022, p. 28). Mostly, CCS is considered necessary to reach national and global climate targets as it is set out to reduce process-related emissions from so-called hard-to-abate sectors, notably the steel, cement, or chemical industry (Martin-Roberts et al., 2021). Yet, although CCS is featured prominently in climate models by the IPCC and the International Energy Agency, "global rates of CCS deployment are far below those in modeled pathways limiting global warming to 1.5°C or 2°C" (IPCC, 2022, p. 28).

One major critique of CCS is that it could lead to or reinforce a carbon lock-in, which means for society to be locked in a system of fossil-based energy sources and production processes that inhibit a fast and effective energy transformation (Asayama, 2021; Janipour et al., 2021; Markusson & Haszeldine, 2009; Sandberg & Krook-Riekkola, 2022; Seto et al., 2016; Shackley & Thompson, 2012; Unruh, 2000; Vergragt, 2012; Vergragt et al., 2011). The main criticism in Germany concerning CCS and carbon lock-in has been that CCS was planned to prolong the lifetime of coal power plants (Erickson et al., 2015; Scott & Geden, 2018), but with the phase-out of coal in Germany this critique does not hold anymore. However, instead of making the discussion on carbon lock-in and CCS redundant, I see a new necessity to discuss the danger of carbon lock-in through CCS. The focus within the lock-in scholarship has moved on to focus on the field of geoengineering and carbon dioxide removal (CDR) techniques, such as bioenergy with CCS (BECCS) or direct air capture with CCS (DACCS) (Cairns, 2014; Carton et al., 2020; Parson & Buck, 2020). However, as new partnerships around CCS emerge, such as the one between Germany and Norway, the danger of carbon lock-in must be evaluated anew, particularly as the field of application has moved away from coal power plants to industrial emissions, gas power plants, and hydrogen production. This new momentum for CCS creates the need to critically analyze the technology, and concrete projects and partnerships provide a new opportunity to discuss CCS in light of real-life examples instead of climate models.

I, therefore, want to fill this research gap and contribute to the CCS and carbon lock-in literature by investigating the risk of lock-in with regard to the new partnership between Germany and Norway.

Concretely, my research question is as follows:

How does the Norwegian-German cooperation on CCS and hydrogen create a carbon lock-in in Germany?

To answer this research question, I will analyze different pillars of carbon lock-in to evaluate how it might manifest in Germany through the German-Norwegian (GER-NOR) cooperation. To this end, I will answer the following sub-research questions:

1. What are concrete CCS and hydrogen projects between Germany and Norway?
2. What investments, infrastructure, laws, and institutions are in place and will be needed to make this cooperation a reality?
3. In what way do the fossil industry and policymakers work together to realize CCS projects?

In the following, I will position this thesis in the field of sustainability science, provide background information on CCS in general, and shortly describe the CCS deal between Norway and Germany. I will then elaborate on the theoretical framework of carbon lock-in and explain my research methodology before analyzing my results and discussing them.

2 Background

2.1 Positioning in sustainability science

Sustainability science "seeks to understand the fundamental character of interactions between nature and society." (Kates et al., 2001). As questions about climate change and climate change mitigation are inseparable from interactions between nature and society, they are at the core of sustainability science. The GER-NOR partnership on CCS and hydrogen is depicted as an important means to mitigate climate change and as such, an analysis of it contributes to the sustainability science literature. Analyzing CCS in particular, raises new questions about nature-society interactions as it opens a new dimension of real or theoretical control over the environment. The option to put CO2 back in the ground supports the idea of technological solutions to anthropogenic climate change and can weaken the urgency and need for drastic changes in the climate change mitigation discourse.

2.2 Development and status quo of carbon capture and storage

In its 2005 special report on carbon capture and storage, the Intergovernmental Panel on Climate Change (IPCC) defined CCS as “a process consisting of the separation of CO2 from industrial and energy-related sources, transport to a storage location and long-term isolation from the atmosphere” (IPCC, 2005, p. 3). Hence, CCS can be applied either to emissions from power plants or to emissions resulting from industrial processes, such as in the cement or steel industry.

The technology for CCS originates in the fossil fuel and chemical industry and has been applied for enhanced oil recovery (EOR) since the 1960s – a process where companies inject CO2 into depleted oil fields to extract more oil than previously possible (Anderson & Newell, 2004; Ma et al., 2022). Until today, EOR is still the primary use of CCS (Bui et al., 2018; Sekera & Lichtenberger, 2020) and as Bäckstrand et al. (2011) put it, CCS could thus “be seen as a continuation of the existing technological trajectory” (p. 276). A milestone in the history of CCS was the Sleipner project in Norway which entered into force in 1996, as it was the first large-scale CCS project that aimed at storing CO2 permanently underground (OECD, 2016).

Since the 2005 IPCC report on CCS, the technology has gained support from governments and organizations, framing it as a bridging technology (Bäckstrand et al., 2011). However, as Lefvert et al. (2022) describe, public support and investments shrank again after the 2009 Copenhagen COP. Furthermore, EU plans to build at least twelve commercial CCS plants by 2015 failed drastically (Scott & Geden, 2018). In general, although the technology exists already for several decades, CCS projects at a commercial scale are scarce and it is therefore still considered an emerging technology (Buck, 2021). While coal power plants were long regarded as one major field of application for CCS in Germany, industry and policymakers moved away from coal and instead imagine CCS to be mainly applied to reduce emissions in so-called hard-to-abate industries that emit CO2 through their production process, such as the cement, steel, and iron industries (Martin-Roberts et al., 2021). In 2021, only 26 large-scale CCS facilities were in operation worldwide (Martin-Roberts et al., 2021).

2.3 The German-Norwegian CCS deal

On 5 January 2023, Germany and Norway published a Joint Declaration about their Partnership on Climate, Renewable Energy, and Green Industry. This partnership includes seven different fields of application, amongst which “Negative emissions / CCS” is one. It comprises the exploration of possible capture, transport, and storage of CO2 at the Norwegian continental shelf (NCS) and the options for transporting CO2 from Germany to Norway, e.g. via pipeline (Office of the Prime Minister & Ministry of Trade, Industry and Fisheries, 2023).

Another aspect of the partnership revolves around hydrogen and is specified in the Joint Statement on hydrogen which was published alongside the Joint Declaration on 5 January. Here the idea is to explore a "large-scale supply of hydrogen with the necessary infrastructure from Norway to Germany by 2030" (Office of the Prime Minister & Ministry of Petroleum and Energy, 2023). As part of this, Norway and Germany commissioned a joint feasibility study to assess both the transport of hydrogen from Norway to Germany as well as the transport of CO2 from Germany to Norway. The study is carried out by DENA, the German Energy Agency, on the German side, and Gassco from the Norwegian side and will be presented in the summer of 2023.

3 Theory

As one main risk of CCS, the following chapter introduces the concept of carbon lock-in, which will be used as the theoretical framework in this thesis.

3.1 Concept of carbon lock-in

The concept of carbon lock-in has been coined by Unruh (2000) who analyzed that "industrial economies have become locked into fossil fuel-based technological systems through a path-dependent process driven by technological and institutional increasing returns to scale" (p. 817). Overall, locked-in systems create systemic barriers to change by upholding the status quo. Path dependency and the process of increasing returns are described by Pierson (2000) as "the probability of further steps along the same path increases with each move down that path. This is because the relative benefits of the current activity compared with other possible options increase over time" (p. 252). Thus, increasing returns processes can also be described as "positive feedback processes" (Pierson, 2000, p. 252).

Applying path dependency to socio-technical lock-in means that one technology has been developed at one point in time, often through mere chance, and over time becomes the "dominant design" (Unruh, 2000, p. 820), posing systemic barriers to adopting alternative technologies, even though they might be superior to the dominant one. In the case of carbon lock-in concretely, this means being locked in a system of fossil-based energy sources and production processes, despite its negative consequences for the environment and people, that impedes the transition to alternative low-carbon or zero-carbon energy sources and products.

There have been several studies developing criteria for assessing the existence of a carbon lock-in (Cairns, 2014; Erickson et al., 2015; Goldstein et al., 2023; Shackley & Thompson, 2012; Trencher et al., 2020; Unruh, 2000; Vergragt et al., 2011; Vergragt, 2012). The conceptualization used in this paper stems from Seto et al. (2016) who did a comprehensive review of the carbon lock-in literature and carved out three main types of lock-in mechanisms: technological & infrastructural, institutional, and behavioral lock-in. On top of these three types of lock-in mechanisms, Buschmann & Oels (2019) emphasize that there is another, often overlooked type: discursive lock-in. They argue that discursive lock-in underlies the other forms of lock-in.

In this paper, I will only analyze technological and infrastructural, as well as institutional lock-in mechanisms. I leave out behavioral lock-in as most of the projects are not yet up and running, so new behavior cannot be observed yet. Discursive lock-in is beyond the scope of this thesis as it would require a whole new set of methods and as space is limited.

In the following, I will explain infrastructural and technological, as well as institutional lock-in in more detail, drawing mainly on explanations by Seto et al. (2016). I will then shortly outline the difference between high- and low-carbon lock-in.

3.1.1 Technological & infrastructural lock-in

The most intuitive type of lock-in relates to the long life and long lead time of technology and infrastructure. This means that not only the long lifetime of physical infrastructure is important but also the fact that large investments are taken, whose returns are expected at a much later point in time. With regards to fossil infrastructure, the basic infrastructure includes for example coal and gas power plants and oil refineries but extends well beyond that. Some more indirect lock-in mechanisms relate to the supporting infrastructure, i.e., pipelines, refineries, gas stations, etc. as they are dependent on the continued use of fossil resources, since otherwise they turn superfluous (Seto et al., 2016). One important concept that Seto et al. (2016) mention here is the idea of "asset specificity" (p. 428), meaning that some infrastructure is unique to one particular usage and cannot be used or retrofitted for alternative purposes. Seto et al. (2016) explain that while fossil power plants already have a long lifetime, what locks in our current fossil-based energy system even more, and what has an even longer lifetime, is energy-demanding infrastructure, i.e., buildings or transportation infrastructure. Another important concept relating to infrastructural lock-in is network externalities (Unruh, 2000), which lead to increasing returns to scale. This means that infrastructure becomes more valuable once it forms a network, e.g. a network of roads makes each road more useful, or a network of telephone numbers makes it more useful for each user to be part of that telecommunication network (Unruh, 2000). Similarly, an existing network of gas pipelines makes the addition of just one more pipeline to another destination easier, less costly, and more profitable than it is to create a whole new transportation system.

When it comes to capital and capital investment, low-carbon energy technology is not an economically viable option as long as fossil options are incentivized and cheaper for industry and fossil fuel companies. Seto et al. (2016) argue that an important lever for change would be climate policies that incentivize the adoption of low-carbon technologies. However, transitioning away from the locked-in fossil infrastructure can create the problem of stranded assets. As Unruh (2019) explains, a stranded asset "is a financial accounting term describing an economic resource that has become non-performing before the end of its useful life" (p. 399). This means that phasing out fossil fuels has huge economic consequences for those that invested in them (Bos & Gupta, 2019). What increases the infrastructural lock-in as described by Bos & Gupta (2019) is that stranded assets from fossil phase-out could have long-term "cascade effects" (p. 4) as they are tied to a deeply interconnected financial network across different carbon-intensive sectors. Hence, infrastructural and technological lock-in is further increased through powerful actors that want to protect their investment in fossil fuels, technology, and infrastructure.

3.1.2 Institutional lock-in

Unruh (2000) differentiates between private and governmental institutions, out of which I will focus on public institutions, following Seto et al.'s (2016) conceptualization of institutional lock-in.

When it comes to public institutions, Seto et al. (2016) firstly point out that lock-in lies within the very design of institutions as they drive to create stability. This differentiates it from technological and infrastructural lock-in, as the initial choice of one technology over another is often the product of chance. This is reiterated by Unruh (2000) who states that public institutions play an important role because they tend to persist for a long time and because they can override market forces, thus influencing the "rules of the game" (p. 824). In institutions, incumbent actors "engage in intentional and coordinated efforts to structure institutional rules, norms, and constraints to promote their goals and interests in ways that would not arise otherwise" (Seto et al., 2016, p. 433). This means that institutional lock-in is automatically beneficial to powerful incumbent actors and that institutions do not necessarily lead to an optimum from a welfare point of view. As institutions strengthen the interests of powerful actors, Seto et al. (2016) explicitly state that institutions act in favor of the fossil industry as "the networks that arise among policymakers, institutional bureaucracies, and powerful energy interests further reinforce and stabilize carbon-intensive systems" (p. 434). Put differently, "[i]nstitutional lock-in exists as institutions strongly discourage and impede change once they are established, and institutions get defended by (a powerful network of) beneficiaries" (Brauers et al., 2021, p. 4). These networks "raise powerful barriers to efforts to get national political institutions to adopt policies that would foster a transition to a lower-carbon trajectory" (Seto et al., 2016, p. 434).

Thus, it is difficult to overcome institutional lock-in from within and Seto et al. (2016) argue that it requires exogenous shocks that open a window of opportunity for new rules and regulations to be developed that favor the interests of different actors.

3.2 Lock-in Mechanisms: Summary

Table 1 summarizes the different mechanisms that determine the risk of technological and infrastructural, as well as institutional carbon lock-in.

Table 1. Summary of technological & infrastructural, and institutional lock-in mechanisms. Own illustration. (Bos & Gupta, 2019; Brauers et al., 2021; Seto et al., 2016; Unruh, 2000, 2019)

Technological and infrastructural Lock-in Mechanisms	Institutional Lock-in Mechanisms
Life and lead time of new and existing infrastructure What is the lead time of new infrastructure, i.e. how long does it take to realize the plans? What is the lifetime of both old and new infrastructure?	**Public institutions, norms, and regulation** Which new institutions need to be formed and which new norms and regulations must come into place to enable the CCS plans?
Asset specificity Can both old and new infrastructure only be used fossil resources or could they be retrofitted for different purposes?	**Policy-industry network** In what way do industry actors and policymakers form a network defending institutions, norms, and regulations that promote CCS?
Network effects Does the planned and existing infrastructure form a network and can thus capitalize on scaling effects?	
Stranded assets Who are the investors in both old and new infrastructure and technology and who risks stranded assets?	

3.3 The problem with CCS and carbon lock-in: High and low carbon lock-in

After showing how a carbon lock-in can unfold, it is important to understand why carbon lock-in is so problematic and to look at it particularly with regard to CCS. As explained in chapter 3.1., one inherent problem about lock-in is that it leads to inertia to change, so even though a transition away from carbon-based industry and energy sources plus CCS might appear as a better option to reaching our climate goals, the hurdles to change will have become too high. Yet, one central argument of CCS promoters is that we need CCS to reach Germany’s climate targets and that emissions in some hard-to-abate sectors are unavoidable. If that were true, it might be in fact necessary to use CCS despite the lock-in mechanisms it unfolds. One could argue that if CCS works the way it is envisioned, i.e., all emissions are effectively stored, then the carbon lock-in is not that problematic, as the CO2 is not released.

Shackley & Thompson (2012) outline two types of lock-in risks related to CCS: A high-carbon fossil fuel lock-in and a low-carbon fossil fuel lock-in. The high carbon lock-in means that new fossil power plants are built with the promise of CCS abating its emissions, but the CSS is never implemented, leading to unabated emissions. A low carbon lock-in means that CCS is implemented, and the emissions are abated, but it still inhibits the use and implementation of alternative energy sources. It is important to reiterate that even if the CCS plans between Germany and Norway work out the way they are designed, and the CO2 is captured and stored, and not emitted, the lock-in still poses barriers to change. Thus, even a low-emission carbon lock-in as laid out by Shackley and Thompson is problematic. However, the even bigger problem would be a high-carbon lock-in, leaving us with unabated CO2 emissions. Shackley & Thompson (2012) argue that the risk of high-carbon lock-in is highest when building CCS-ready power plants – a fossil power plant with installations that could, at some point in the future, capture its CO2. As Asayama (2021) points out, drawing on Markusson & Haszeldine (2009), "the only safe way to make sure to avoid this risk of unabated carbon lock-in is to not build new fossil plants in the first place." (Asayama, 2021, p. 4).

In addition, there are more ways in which CCS can lead to a high-carbon lock-in, i.e., a lock-in situation in which not all emissions are abated as promised or planned. As Sekera and Lichtenberger (2020) point out, CCS does not necessarily result in a net-zero emission balance as the whole life cycle process of CCS produces emissions as well. Lastly, even if emissions are successfully captured without producing additional CO2, the risk of leakage remains. And although sites have been monitored for several years already (e.g. at the Sleipner project for over 20 years), nobody knows what will happen with the CO2, 100 or 200 years from now.

4 Methodology

In this thesis, I applied a critical realist approach. The assumption underlying this epistemology is that the real or objective world cannot be directly observed and that there are unobservable structures that shape the reality that can be perceived. Therefore, studying the context of an observed phenomenon is important as it reveals these structures (Bryman, 2012). Studying some of the technological and infrastructural lock-in mechanisms focuses less on underlying structures and more on directly observable realities, like the chemical properties of different gases and how a pipeline to transport these must be built. This applies mostly to life and lead time, asset specificity, and network effect of physical infrastructure. However, when studying the risk of stranded assets and the institutional lock-in mechanisms, applying a critical realist lens is important as underlying power structures, such as networks between industry and policymakers, might not be directly observable.

Thus, the lock-in mechanisms are studied qualitatively, using two qualitative research methods: A qualitative content analysis of documents, as well as complementary semi-structured interviews (Bryman, 2012). The document analysis is not restricted to any specific type of document but comprises all publicly available sources, both from state actors, as well as industry and private actors. I analyze publicly available material of any kind in English and German. The reason for using documents as data sources is that the GER-NOR partnership is yet to be materialized and thus gathering data from state and industry sources provides important insights into different plans for future CCS- & hydrogen developments. A qualitative content analysis "comprises a searching-out of underlying themes in the materials being analyzed" (Bryman, 2012, p. 557). I draw the themes for my analysis from the theory on carbon lock-in, restricting my analysis to technological and infrastructural, and institutional lock-in. The themes are already explained in the theory chapter and are illustrated in Table 1.

Before diving into the content analysis, I conducted a mapping of the different CCS-related projects between Germany and Norway as they form the subject of my analysis and answer my first sub-research question. The mapping aimed at getting an overview of the most prominent projects including the most powerful actors. I identified those by looking for projects that involve big companies or that were directly mentioned in articles or other documents that discuss the GER-NOR partnership.

In addition to the document analysis, I chose to conduct semi-structured interviews with the most relevant actors from both government and industry. As I am looking at a topic that mostly consists of plans for the future that are not materialized yet, the publicly available information is limited. Furthermore, as I am applying a critical realist lens, I hoped to gain further insights into underlying networks, relations, or other structures that cannot be deducted from the documents. Thus, the goal behind the interviews was to firstly verify some of the information I found in the documents, and secondly, to get additional information and clarify some questions or inconsistencies with regards to the partnership. My outreach and correspondence with the different actors are summarized in Table 2.

Concerning the unit of analysis, this thesis follows a "cross-sectional design with case study elements" (Bryman, 2012). It is cross-sectional as it points to the risk of carbon lock-in through CCS and particularly through CCS-related international partnerships. These are not unique to Germany and Norway and some of the results can bear important learnings for other countries. The case study elements include that in some instances, the uniqueness of Germany in this regard is outlined, e.g., when looking at the specific political and legal context or when discussing some implications of a carbon lock-in.

Table 2. Summary of outreach to and correspondence with actors. Source and illustration: author.

Company / Organization	Relevance	Correspondence
The German Federal Ministry for Economic Affairs and Climate Action (BMWK)	German government body and signatory to the political partnership with Norway.	One background dialogue and one interview: Interview BMWK (2023)
Equinor	Norwegian fossil fuel major with CCS- and hydrogen partnership with RWE, Wintershall Dea, and OGE.	Interview with one representative: Interview Equinor (2023)
RWE	German fossil fuel major in CCS- and hydrogen partnership with Equinor.	Email correspondence, but no interview
OGE (Open Grid Europe)	Largest gas transmission operator in Germany with CCS- and hydrogen projects planned.	Interview with one representative: Interview OGE (2023)
Wintershall Dea	Major fossil gas and crude oil producer internationally. CCS – and hydrogen projects with RWE and several other actors.	No answer to interview request
German-Norwegian Chamber of Commerce (AHK)	Industry association between Germany and Norway seemingly playing a role in facilitating the conclusion of the partnership.	Written answer to interview questions: Answers AHK (2023)
DENA (German Energy Agency)	Assigned to conduct the feasibility study for the GER-NOR partnership for the German side.	Answer that they cannot provide information before the publication of the feasibility study
Gassco	Assigned to conduct the feasibility study for the GER-NOR partnership for the Norwegian side.	No answer to interview request

5 Analysis

The analysis is structured into a chapter identifying relevant CCS- and hydrogen projects between Germany and Norway to then in the next section look at the different themes of the qualitative content analysis, covering the two lock-in mechanisms of infrastructural & technological and institutional lock-in. The goal is to answer the question in what way the GER-NOR partnership creates or reinforces carbon lock-in mechanisms in Germany, with the three sub-research questions being answered along the way.

5.1 Concrete CCS-related projects and plans between Germany and Norway

The Joint Declaration on the GER-NOR Partnership on Climate, Renewable Energy and Green Industry from 5 January 2023 outlines the broad political agreement between the two countries on CCS: They agree for Germany to transport CO2 to Norway, for it to be stored at the NCS. For this to be developed further, it says that the parties “will discuss various options for CO2 infrastructure value chains, including a CO2 pipeline from Germany and Norway.” (Office of the Prime Minister & Ministry of Trade, Industry and Fisheries, 2023, p. 3). Furthermore, their Joint Statement on Hydrogen is relevant to the topic of CCS as the plan foresees to, “for a transition period”, supply Germany with blue hydrogen from Norway, i.e., hydrogen produced from fossil gas with CCS (Office of the Prime Minister & Ministry of Petroleum and Energy, 2023, p. 2). Thus, as CCS is at the basis of the production of blue hydrogen, any hydrogen project that touches upon the use of blue hydrogen will be considered in this paper as well, in addition to CO2 capture, transportation, and storage projects.

The political cooperation between Germany and Norway with regard to CCS and hydrogen already started before January 2023. German Chancellor Olaf Scholz visited Oslo already in August 2022 to discuss the future of the GER-NOR energy relations and new challenges in the face of Russia’s war against Ukraine. Amongst other things, they declared they would “further deepen their energy and climate cooperation across the board, including offshore wind power, solar energy, hydrogen, and carbon capture and storage” (Wehrmann, 2022).

However, neither press releases from the summer of 2022 nor the two documents – the Joint Statement and the Joint Declaration – provide insights into the practicalities of the partnership, i.e., what is going to be built, when by whom, etc. Thus, in order to understand which concrete projects are being planned, it is necessary to turn to industry actors. In the following, I will list the most prominent concrete industry partnerships that connect Germany and Norway and contain either CCS or blue hydrogen plans.

5.1.1 Equinor & RWE – Blue hydrogen

The first industry partnership that is closely connected to the political partnership declared on 5 January 2023 is the one between Equinor and RWE, as they signed an agreement “to jointly develop large-scale energy value chains, building on the partnership between Norway and Germany” (Equinor, 2023). Equinor and RWE signed the agreement on 5 January, in the presence of German minister for economic affairs and climate action Robert Habeck and Norwegian Prime Minister Jonas Gahr Støre. Equinor is a Norwegian state-owned energy company, extracting oil and gas for over 50 years and RWE is a major German energy company founded in 1898 and operating internationally.

Their deal from 5 January states that they want to build hydrogen-ready new gas power plants in Germany, “which will be initially fueled with natural gas and then gradually use hydrogen when volumes and technology are available” (Equinor, 2023). To that end, they want to build facilities in Norway to produce blue hydrogen from fossil gas using CCS and storing the CO2 offshore Norway. The hydrogen should then be transported from Norway to Germany via pipeline. Further, the plan includes the development of offshore wind farms in order to provide for the production of green hydrogen in the future (Equinor, 2023). The project is illustrated in Appendix A.

5.1.2 Equinor & Wintershall Dea – CCS

Another project which Equinor is involved in is a CCS project with Wintershall Dea. Wintershall Dea is a major fossil gas and crude oil producer and operates worldwide in oil and gas production.

They plan to build a large-scale CCS infrastructure to transport, inject, and store German CO2 emissions in Norway (Equinor, 2022). The goal is to build a 900-kilometer-long pipeline connecting a German collection hub and Norwegian storage sites before 2032. They expect to transport 20 to 40 million tons of CO2 per year by 2037. The CO2 that will be transported is supposed to stem from “carbon-intensive industries that need safe and large-scale underground CO2 storage to abate unavoidable emissions from their processes” (Equinor, 2022) (see Appendix B).

5.1.3 Wintershall Dea & NWO – Blue hydrogen

Wintershall Dea further signed an agreement with German pipeline operator Nord-West Oelleitung (NWO) for the BlueHyNow hydrogen production plant in Wilhelmshaven. The goal is to produce blue hydrogen in Germany with fossil gas from Norway and to store the CO2 in storage sites in both Norway and Denmark (Pekic, 2022).

5.1.4 OGE (Open Grid Europe) – CO2 value chain

OGE (Open Grid Europe) operates Germany’s largest fossil gas pipeline network and is one of the leading European gas transmission system operators.

OGE plans to build a CO2 grid across Germany, with a 964-kilometer-long starter grid and a transportation capacity of 18.8 million tons of CO2. As CO2 sources, they mainly consider so-called hard-to-abate sectors. i.e., the cement, steel, and chemical industries. But they also include biological sources, CO2 from DACCS, or from gas-fired power plants. Their goal is not only to store the CO2 but to use it as well, so-called carbon capture and use (CCU). The CO2 can be used as an energy carrier, as material (e.g., in chemicals, solvents, etc.), or physically (e.g., in sparkling beverages or fire extinguishers). They aim to create a circular economy with CO2 through carbon capture use and storage (CCUS) (see Appendix C) (OGE, 2023b). The project description does not mention where the

CO2 will be stored, but one interviewee said that they are flexible as to where the CO2 will be stored. They merely transport it to possible export stations, e.g., in Wilhelmshaven, and do not have any priority as to the location of storage (Interview OGE, 2023). However, as one major partner to store German CO2 is Norway, it is not unlikely to assume that at least parts of the CO2 transported by OGE will end up in Norway.

5.1.5 OGE & Equinor – Blue hydrogen

OGE and Equinor further plan several hydrogen projects in Germany, with the H2morrow project having concrete ties to Norway. The project's plan is for Norway to transport fossil gas to Germany, where it should be reformed to blue hydrogen, with the CO2 being transported back for storage to Norway. OGE claims that already this decade industry and other end users in North Rhine-Westphalia should be supplied with 8.6 terawatt hours of blue hydrogen. The H2morrow project is described by OGE as to "provide the impetus for a large-scale, diversified hydrogen market across all sectors in Germany" (OGE, 2023a).

5.1.6 Summary table: Concrete CCS- and hydrogen projects

Table 3. Summary of the most important CCS- and hydrogen projects between Germany and Norway. Illustration: author.

Companies / Organizations	Project description
Equinor & RWE	• Build new hydrogen-ready gas power plants in Germany • Produce blue hydrogen in Norway to be transported to Germany via pipeline • Provide the new power plants with fossil gas first, then with blue hydrogen, and eventually phase in green hydrogen if available (Equinor, 2023)
Equinor & Wintershall Dea	• Large-scale CCS infrastructure to transport, inject, and store German CO2 emissions in Norway • 900-kilometer-long pipeline between Germany and Norway • For "unavoidable" emissions from carbon-intensive industries (Equinor, 2022)
Wintershall Dea & NWO	• BlueHyNow hydrogen production plant in Germany • Produce blue hydrogen in Germany with fossil gas from Norway • Transport and store CO2 from hydrogen production in Norway & Denmark (Pekic, 2022)
OGE (Open Grid Europe)	• CO2 grid across Germany • Circular economy with CO2 with CCUS • Primarily industry emissions but possible sources also e.g., gas-fired power plants (OGE, 2023b)
OGE & Equinor	• H2morrow project: transportation of fossil gas from Norway to Germany • Reformation to blue hydrogen in Germany • Transport back CO2 to Norway for storage (OGE, 2023a)

5.2 What are CCS and hydrogen being used for?

To properly analyze how a carbon lock-in is created it is important to know which emissions CCS and CCUS are planned to be used for. The same goes for the hydrogen projects. It is important to understand how the hydrogen will be produced and what it will be used for.

For CCS, it became clear that the German government is focusing on the so-called unavoidable emissions from hard-to-abate industries, i.e., cement, steel, and waste incineration (Interview BMWK, 2023). However, while OGE's plans for a CO2 grid also focus on industry emissions, they do not exclude emissions from fossil energy sources (Interview OGE, 2023; OGE, 2023b). When confronting my interview partner at the BMWK with the question of whether they can imagine CCS also being used for fossil energy production, they said that the plan is to start with hard-to-abate industries. However, once the infrastructure is there and everything starts to work properly, they said that using it also for the energy sector is present in the back of their minds when creating the Carbon Management Strategy and while it not being the focus, they did not clearly exclude this option (Interview BMWK, 2023). Furthermore, both OGE and the BMWK are planning to employ carbon capture use and storage (CCUS) (Interview BMWK 2023; OGE, 2023b), which opens yet other important questions of carbon lock-in and the secure sequestration and storage of CO2.

When it comes to hydrogen, all major industry players included in this thesis plan to first employ blue hydrogen, without concrete plans to phase in green hydrogen soon (Equinor, 2023; OGE, 2023a; Pekic, 2022). While the Joint Statement from Germany and Norway claims that "[g]reen hydrogen can subsequently be phased in into the common transport infrastructure" (Office of the Prime Minister & Ministry of Petroleum and Energy, 2023), they don't provide any specific timeline for when they are aiming to do so. Furthermore, RWE and Equinor plan to build new hydrogen-ready gas power plants, which will first run on fossil gas (Equinor, 2023).

It thus becomes clear that there is a risk for carbon lock-in through CCS in different ways:

- locking in industrial processes that produce CO2 instead of switching to alternative products;
- locking in fossil-based energy sources through CCS;
- locking in CO2 and CCS through a CCUS cycle that is difficult to break up once established;
- and locking in the use of fossil gas and fossil gas power plants through the production of blue hydrogen and the promise of hydrogen-ready power plants.

The next two chapters will dive deeper into the question of how exactly infrastructural and technological, as well as institutional lock-in mechanisms are created through these projects.

5.3 Infrastructural & technological lock-in

To analyze how the German-Norwegian Partnership creates an infrastructural & technological carbon lock-in in Germany, this chapter will examine the abovementioned CCS- and hydrogen projects according to the four themes identified in the lock-in literature: Life and lead time of new and existing infrastructure, asset specificity, network effects, and stranded assets.

5.3.1 Life and lead time of existing and new infrastructure

Both life and lead time of fossil infrastructure, as well as supporting infrastructure, are important factors with regard to carbon lock-in. As explained in the theory chapter, lead time refers to the time from the investment decision to the fulfillment of an infrastructure project. The longer both life and lead time, the higher the risk of carbon lock-in.

There is different infrastructure that needs to be built or repurposed in order to realize the different projects. There are on the one hand the new hydrogen-ready gas power plants and hydrogen reformers as direct infrastructure, but most prominently the supporting infrastructure in the form of pipelines and storage hubs in Germany. It is unclear whether the different projects are going to use the same pipeline or different pipelines to transport CO2 from Germany to Norway or to transport hydrogen to Germany, but as Equinor will most likely be involved in all of these pipeline projects in one way or another, the interview with a representative from Equinor provides the most useful insights into their pipeline plans.

When it comes to the lead time of these pipelines it is firstly important to know that Equinor is considering repurposing one of the three existing pipelines that currently connect Norway and Germany. However, they were not certain yet, whether they will repurpose an existing pipeline or build a new one. When asked when the pipeline would be ready, either repurposed or new, my interview partner responded that the goal is to have them in operation by 2030. However, they mentioned that there are uncertainties as to the potential finishing date as many different things need to be in place: the design, the engineering, the steel production, the shipping, etc. Therefore, they were rather vague in their answer of when the pipeline can be expected to be operated and could not settle on a certain date. When it comes to the lifetime of a pipeline, the picture was rather clear: they referred to how the oldest gas pipeline from Norway to Germany, Norpipe, has been operating since 1977, and that the pipelines have a lifetime far beyond the resources in the oil and gas fields. In terms of CCS, they argued that the issue won’t be the pipelines but rather the storage sites that fill up over time, although they were confident that there are enough possible storage sites available for a long time. They said that to do an investment decision they expect the facilities to be operated for at least 20 years (Interview Equinor, 2023). This means that taken together, lead and lifetime of one pipeline only would have to take until 2050 in order to be profitable for Equinor, with an expected lifetime of the pipelines to far exceed 2050.

When it comes to the project between RWE and Equinor to build H2-ready gas-fired power plants, my interview partner at Equinor stated that they were only in the early days of this cooperation and could thus not provide any timeframe, neither by when they are planning to have built the power plants, nor when the blue hydrogen should be phased in. Thus, they also do not have any date in mind when it comes to phasing in green hydrogen. They also mentioned that to this day the production of gas turbines that can burn 100% hydrogen is still in the making (Interview Equinor, 2023). In their project illustration (Appendix A), they create the image that the plants should be up and running by 2030. Throughout the interview, it became clear however that they do not have a clear timeline with regard to when they want to replace fossil gas with blue hydrogen or green hydrogen. Thus, what this project consists of is the construction of new gas-fired power plants in Germany, with no clear plan as to when they should stop being fueled with fossil gas or blue hydrogen.

In addition to the pipelines, new storage sites need to be explored and storage facilities built. My interview partner at Equinor said that they got licenses for new storage sites in Norway that do not belong to the Northern Lights CCS project (Interview Equinor, 2023). This means that on top of the pipeline construction, all necessary plants at the new storage sites need to be built as well.

In general, what struck me particularly during my interview with Equinor was how the projects were referred to as still being at the very start with many open questions to be decided upon. My interview partner at the BWMK confirmed this, saying that they are still doing the feasibility study and that even when they decide to support a pipeline project, there follows a lead time of several years. They also said explicitly that CCS in Germany for emissions from industry is planned to be a long-term endeavor, planned at least until 2045-2050 (Interview BMWK, 2023). Furthermore, when looking at the project between Equinor and Wintershall Dea, they state on the one hand that they want to connect Germany and Norway with a CO2 pipeline before 2032, but on the other hand mention a pipeline capacity of 20 to 40 million tons CO2 per year by 2037 (Equinor, 2022). It is thus also unclear by when they plan to have CO2 running through their pipelines.

Overall, it can be summarized that none of the projects will be operational before 2030, that they are all built with the idea to be operated long-term, and that the use of a CO2 pipeline for less than 20 years would not be economical for the companies involved.

5.3.2 Asset specificity

On top of life and lead time of the infrastructure, it is important to look at its asset specificity, i.e., whether it could be retrofitted or repurposed or whether it is tied to one use or product.

When it comes to pipelines, it is generally possible to repurpose fossil gas pipelines to hydrogen or CO2 pipelines. Jayanti (2022) even calls it the “most promising approach […] for moving hydrogen” (p. 815). Some technical challenges are that fossil gas compressors need to be replaced with hydrogen-specific compressors and that due to their different densities, fossil gas and hydrogen need to be pressurized to different levels if they ought to be transported via the same pipeline (Jayanti, 2022). When it comes to pipelines specifically built to transport hydrogen, it does not matter whether they transport green or blue hydrogen, as, once produced, hydrogen is hydrogen (Interview Equinor, 2023). However, while the pipelines can in principle be repurposed without major new investments, the production of hydrogen differs from blue to green. Whereas the production of blue hydrogen requires a steam reformer to reform the fossil gas into hydrogen, a completely different plant is required for green hydrogen. In that process, an electrolyzer is used to create hydrogen from water (see illustration in Appendix D) (Iberdrola, 2023). Thus, the reformers are specific to producing blue hydrogen and cannot be used to produce green hydrogen.

All in all, while the possibility to repurpose pipelines exists, some adjustments would need to be made for pipelines to transport something else than fossil gas. Mostly, however, to switch to green hydrogen, new production devices need to be built. Furthermore, the CO2 capture and storage sites that are being explored and built now have the sole purpose of storing CO2 and would become completely redundant if we phased out CCS again.

5.3.3 Network effects

Lock-in effects are further enhanced if the infrastructure, both old and newly built, creates a network and can thus capitalize on the economies of scale.

In the case of repurposing existing fossil gas pipelines, it is clear that the CCS and hydrogen projects make use of an already existing network. The best illustration of network formation is the CO2 grid project by OGE: They are planning to connect not only the different CO2 pipelines with a collection hub in Germany but also to connect the grid to the different capture and use sites for CCU (OGE, 2023b). This grid will be mostly built from scratch as they plan to transport CO2 in liquid form, which requires new pipelines (Interview OGE, 2023). However, the hydrogen infrastructure will mainly repurpose old fossil gas pipelines, so they can also make use of an existing network of fossil pipelines (Interview OGE, 2023). As the CO2 capture sites will be CO2-producing industry actors, such as cement or steel production plants, they will profit from the network as well. Given that OGE plans to create a CO2 circular economy with carbon capture use and storage, they heavily rely on building a network that will be difficult to break up again as it would ruin the entire cycle. Connecting both CO2 emitters and CO2 users in a cycle makes it easier and cheaper to connect an additional customer and thus incentivizes the CO2 network to grow.

Thus, one can conclude that already the first CO2 and hydrogen transportation projects can make use of an existing infrastructure of pipelines. The network effects will unfold properly once the first pipelines are built as it will then be very easy to connect a new industry or power plant to the network at low costs.

5.3.4 Stranded assets

When looking at the risk of stranded assets, one must look at the lifetime of existing and planned infrastructure or resources. It became clear during the interview with Equinor that they only used around 50% of their fossil gas resources available (Interview Equinor, 2023). This means that phasing out fossil gas creates stranded assets from their point of view as they would leave around 50% of their assets unused. My interview partner at Equinor clearly expressed that as long as they have a "CO2 solution" through CCS, they do not see why they would need to leave the rest of their reserves untouched, as the problem was not the fossil gas but the CO2. So, once they found a CO2 solution, they see no problem in using up the rest of their reserves (Interview Equinor, 2023).

Furthermore, the long life and lead time of the CCS- and hydrogen infrastructure create the risk of stranded assets. If companies, and the German state, take the investment decision today to invest in CCS- and hydrogen, changing these plans would create stranded assets for everybody involved. This leads us to a path where, unless we operate the CCS- and hydrogen infrastructure until at least around 2050, stranded assets are created.

Furthermore, the topic of stranded assets opens up the whole discussion about so-called "hard-to-abate" sectors and "unavoidable" emissions, as is often referred to when talking about the steel or cement industry. Without CCS these industries risk stranded assets as the other option to reducing emissions from these industries is to phase them out altogether.

5.4 Institutional lock-in

This section will analyze in what way the CCS- and hydrogen projects create institutional lock-in by looking into the two factors identified in the theory: Public institutions, norms, and regulation, and policy-industry network.

5.4.1 Public institutions, norms, and regulation

As described in the theory chapter, once created, institutions, norms, and regulations create lock-in effects as institutions purposefully create inertia to change.

Although there is much geological potential for storage sites, CCS is currently de facto not possible in Germany. The sequestration of CO2 is regulated in the Bundesemissionsschutzgesetz (BimSchG), a law protecting against harmful effects on the environment caused by air pollution. In addition, the Kohlendioxid-Speicherungsgesetz (KSpG) that entered into force in 2012 regulates the transport and storage of CO2. Since 2012, the KSpG allows research, testing, and demonstration of CCS in a limited manner (Umweltbundesamt, 2022). Furthermore, it is within the jurisdiction of the Bundesländer in Germany to evaluate in which areas demonstration projects should be allowed. Most Bundesländer however have been strictly against allowing CCS on their territory (dpa, 2012). According to the KSpG, in order to store CO2 in Germany, requests for storage sites needed to be issued by the end of 2016. Since no request has been issued until the deadline, it is currently impossible for any storage site to be explored. There has been one test area for CCS in Germany, in Ketzin. From 2004-2017, 70.000 tons CO2 were stored at the site and the final report evaluated the test as successful and the storage as safe (Deutsches GeoForschungsZentrum, 2018; Vallentin, 2022).

The KSpG must be reevaluated every four years and the recent evaluation in December 2022 includes some important developments. While emphasizing that to meet Germany's climate goals, emission reduction and avoidance plus increased efficiency are the number one priority, the report states that CCS will also be necessary to reach climate neutrality by 2045 (Bundesministerium für Wirtschaft und Klimaschutz, 2022b). Therefore, the report suggests adapting the German legal landscape to enable CO2 transport and its necessary infrastructure. To that end, the German government is currently working on a Carbon Management Strategy which is supposed to answer questions regarding areas of application of CCS, transport, and infrastructure (Bundesministerium für Wirtschaft und Klimaschutz, 2022a). During my interview with the BMWK, it became clear that the goal of the Carbon Management Strategy is to on the one hand determine the necessity of CCS for Germany, including capture sites, transportation, and storage potential in Germany, but also to then create the necessary regulatory frameworks and norms to enable CCS (Interview BWMK, 2023). The written answers to my questions by the German-Norwegian Chamber of Commerce affirmed this by writing that a "legal framework that allows for German exports of CO2 is expected to be the single most important change in the legislation" (Answers AHK, 2023). Thus, it can be expected that a CCS- and potentially blue hydrogen-enabling regulatory framework will become a reality in Germany soon.

However, to realize the transboundary projects with Norway, international transportation must be possible. Therefore, another important law is the London Protocol, which entered into force in 2006 and aims at reducing marine pollution. Article 6 of the protocol prohibits “the export of wastes or other matter to other countries for dumping or incineration at sea” (London Protocol, 2006). As carbon dioxide is considered waste in that agreement, the international transport of CO2, e.g., via pipeline for the purpose of CCS is currently not allowed. Therefore, an amendment to Article 6 has been made that creates an exception for CO2 and allows for international CO2 transfer and storage. However, my interview partner at the BMWK stated that they are currently discussing the ratification of the London protocol and other legal options to make CO2 transportation possible, for example via bilateral contracts (Interview BWMK, 2023).

To conclude, Germany is currently producing a Carbon Management Strategy to remove the regulatory barriers to CO2 transportation and infrastructure in Germany and is also considering the ratification of the amendment to the London protocol to allow for transnational transportation of CO2.

5.4.2 Policy-industry network

As explained in the theory chapter, institutional lock-in is further intensified and further serves incumbent actors’ interests when a network of powerful public and private actors is formed that supports the carbon-prolonging institutions. Thus, this chapter will analyze the existence of these networks and how policy and industry interact in the field of CCS and hydrogen.

The Joint Statement on hydrogen states that there will be a feasibility study carried out by Gassco and DENA, including many industrial partners, to assess both the supply of hydrogen from Norway to Germany, as well as the transport and storage of CO2 from Germany to Norway (Office of the Prime Minister & Ministry of Petroleum and Energy, 2023). Although it should have been published in spring 2023, the study is not available yet. I tried to contact both DENA on the German side as well as Gassco on the Norwegian side and only got an answer by email from DENA saying that until the study is finished in the summer, they are not authorized to provide me with any information about the content or process of the study (DENA, 2023). It is however interesting to look at both DENA and Gassco and other actors involved in these sorts of feasibility studies. Gassco is a Norwegian operator of natural gas pipelines and can thus be considered an integral part of the Norwegian fossil industry. DENA, a German service company with the purpose to promote and shape German policy goals in terms of climate protection and energy transition, already published a study in October 2021 about how to reach climate neutrality in Germany (Deutsche Energie-Agentur GmbH, 2021). An interim report about the study, as well as the final study, have been criticized as one-sided and financed mostly by companies from the oil and gas industry (LobbyControl, 2021). As it already says in the Joint Statement, “a large number of industrial partners” will be involved in this new study, so it will be interesting to see if the same criticism will hold true for the new study as well (Office of the Prime Minister & Ministry of Petroleum and Energy, 2023).

However, it is not only feasibility studies where oil and gas companies and other industry actors play an important role. Within the German-Norwegian Chamber of Commerce (AHK), industry and government representatives come together to discuss CCS and hydrogen-related issues, for example in the format of the German-Norwegian Energy Dialogue, organized by the AHK (AHK, 2022). Their role is to facilitate dialogue between political decision-makers and industry, and they can mobilize senior politicians. This year in January for example, they hosted a round table discussion between Robert Habeck, the German Minister for Economic Affairs and Climate Action, Jan Christian Vestre, the Norwegian Minister of Trade and Industry, and several German and Norwegian business representatives (Answers AHK, 2023). It can thus be said that the AHK provides structures for industry and the public sector to form a network and come together to discuss important issues, such as the development of CCS and hydrogen.

In addition, industry representatives are also part of the new Carbon Management Strategy that is created by the German government at the moment. My interview partner at OGE said that while it was predominantly associations and NGOs to take part in the discussions, the government is inviting industry players as a next step. Although I cannot say for sure who was invited to these discussions after all, I can say that OGE was hoping to get invited (Interview OGE, 2023). It also became clear during my interview with the BMWK that they see a need to talk to industry actors as these will be the ones to ultimately implement the political plans and ambitions (Interview BWMK, 2023). Therefore, there exists a reciprocal relationship between industry and state: The state needs the industry to turn its plans into action, and the industry needs the state to provide the regulatory framework to enable them to do so. As my interview partner at Equinor described it, the role of a political agreement such as the one on 5 January between Norway and Germany is to de-risk decisions and investments for the industry by showing the direction in which the political landscape is moving (Interview Equinor, 2023).

It can thus be summarized that there exists a strong network between powerful industry actors and state actors when it comes to CCS and hydrogen. This is already becoming obvious when looking at the list of companies that are now considering CCS and hydrogen projects as they are all major oil and gas companies.

5.5 Summary lock-in mechanisms

The analysis has shown which concrete CCS and hydrogen projects are planned between Germany and Norway and for which purposes. In terms of the concrete lock-in mechanisms, the results reveal that the CCS and hydrogen plans will create both infrastructural and technological, as well as institutional lock-in effects.

The infrastructural and technological lock-in effects mainly unfold through the long life and lead time of, and high investments in the infrastructure. These investments create the risk of stranded assets. Furthermore, it became clear that for example, Equinor wants to use blue hydrogen to make further use of their fossil gas assets. In addition, the infrastructure can capitalize on network effects which further increases scaling effects. When it comes to asset specificity, the lock-in risk is not that high as theoretically both CO2 and hydrogen pipelines can be used for green hydrogen at some point. However, some infrastructure is specific to fossil gas, such as blue hydrogen steam reformers.

The institutional lock-in effects result from the planned change in legal infrastructure enabling international CO2 transportation and are enhanced through a strong policy-industry network supporting CCS and hydrogen plans and projects.

6 Discussion

In the following chapter, I will discuss my results in light of four themes: high and low carbon lock-in, so-called unavoidable emissions, mitigation deterrence, and negative externalities from fossil fuel use.

6.1 High and low carbon lock-in

The results show how the different CCS- and hydrogen-related projects between Germany and Norway create a carbon lock-in. However, as described in Chapter 3.3, Shackley & Thompson (2012) further differentiate between a high and a low carbon lock-in. They state that the risk for high carbon lock-in is highest when CCS-ready power plants are built. While my thesis does not include any CCS-ready power plant projects, it does include the hydrogen-ready power plants planned by RWE and Equinor. I argue that the danger of high carbon lock-in exists just as much for hydrogen-ready power plants as for CCS-ready power plants, as ultimately, we don’t know for certain if and when and to what extent the fossil gas will be replaced by hydrogen. The success of these power plants to run on blue or green hydrogen is not guaranteed at the point when the plants are built. This could perhaps be alleviated if RWE and Equinor at least had a clear timeline in mind for when and how they are phasing in hydrogen, but as my results have shown, this is not the case. Therefore, the project between RWE and Equinor clearly risks a high carbon lock-in, i.e., a lock-in situation with unabated emissions.

Another way to end up in a high carbon lock-in, as described in Chapter 3.3, is when not all emissions are captured and stored as planned. One situation in which leakages occur is already the gas extraction. When the fossil gas is derived from fracking, leakages already occur at the extraction site. When applying CCS, the question about capturing and binding CO2 forever is particularly relevant when talking about CCU or CCUS (referred to as CCU(S) in this chapter). When CO2 is captured and used in products, it can easily be released again when these products are thrown away and are not included in a closed CO2 cycle. Securing that CO2 does not escape this cycle and is not ultimately released into the atmosphere is even more difficult with CCU(S) than with CCS as it would require a closed cycle where all the products included are monitored and recycled. This would in practice mean that we need to install carbon capture equipment at all waste incineration plants or use CDR technologies to remove remaining CO2 from the atmosphere. My interviewee at OGE pointed out that holes in a CO2 cycle should be compensated by either using biogenic CO2 or through direct air capture (Interview OGE, 2023). This shows how the risk of leakages is recognized, but instead of considering not to do CCU(S), yet another patch is planned to be used – this time in the form of CDR technologies that are supposed to suck the escaped CO2 from the atmosphere.

My interviewee at the BMWK pointed out that it will be important to ensure that CO2 is permanently or long-term bound in a product. However, they also said that the government will not dictate the industry, which products they are allowed to integrate in a CCU(S) cycle. They explained that they expect this regulation to happen indirectly through financing or recognition of certificates so that companies would have an economic incentive to aim for long-term CO2-binding products (Interview BMWK, 2023). This goes to show that although political decision-makers are aware of the risk for CCU(S) to only store CO2 in the short term, the regulation of this problem is left to the market. Currently, there is no plan for consistent regulation of CCU(S) from the German government. Thus, I see a high risk for CCU(S) to result in a high carbon lock-in, with emissions bound in products to be released again. This would merely shift the problem of unabated emissions to the future and other sectors, such as the waste sector, while we need urgent and drastic CO2 reductions now.

6.2 Hard-to-abate sectors, unavoidable emissions, and the need for CCS in Germany

Another crucial discussion point is that CCS in Germany is envisioned mainly for so-called hard-to-abate industries. While the expression “hard-to-abate” only denotes that emission reduction will be difficult, it is often used interchangeably with the expression “unavoidable emissions”, which expresses with certainty that emission reductions will not be possible. Paltsev et al. (2021) describe that an industry is hard-to-abate when a shift to low-carbon energy inputs can reduce the energy-related emission but not the process emissions. The most prominent ones are the steel, cement, and chemical industries.

When it comes to steel production, the idea that it produces unavoidable emissions is not true. Recent studies conclude that steel production can be fossil-free with hydrogen direct reduction (HDI) (Lopez et al., 2023; Müller et al., 2021; Öhman et al., 2022; Otto et al., 2017; Pimm et al., 2021; Vogl et al., 2018). Through HDI, almost 100% of CO2 emissions from the steel industry are avoidable and a fossil-free production of steel can even be commercially competitive if the CO2 price is high enough (Vogl et al., 2018).

In the cement industry, process emissions arise from the calcination of limestone, which is why the only way of producing cement emission-free is by capturing the CO2 emissions (Rumayor et al., 2022). However, while it might be true that emissions from cement production are unavoidable, the question arises whether the production of cement is unavoidable too. Cement is mainly used to create concrete, the second most used material or resource after water globally (Vijayan et al., 2020). There exists a lot of research on substitute materials (Qureshi et al., 2022), and replacing cement with other materials was also picked up by my interview partner at the BMWK, who said that "of course we can decide that we don't want to have concrete anymore, that we build roads out of something else and replace cement with something else, that's currently not foreseeable at all and extremely unlikely". (Interview BMWK, 2023, translated with DeepL). This goes to show that what is often referred to as "unavoidable" is rather based on economic and political decision making than objective facts. The quote by my interviewee shows an awareness that we could theoretically move away from using cement to reduce emissions, but that there is either no political or economic will to do so.

A last look at the chemical industry paints a similar picture. Isella & Manca (2022) identify the chemical and petrochemical industry as the top emitter among all industry sectors. The products include "fertilizers, pesticides, pharmaceuticals, plastics, resins, refrigerants, paints, solvents, soaps, perfumes, and synthetic fibers, as well as chemicals derived from oil refining" (Isella & Manca, 2022, p. 4). I want to raise a similar question as with regards to cement: Is there a way to replace and recycle these chemical products altogether instead of trying to decarbonize their production through CCS? As my results show, OGE wants to create a huge carbon cycle to keep up the production in so-called hard-to-abate industries. However, instead of creating a huge carbon cycle, where CO2 is captured and then introduced as a resource to produce new chemicals, could we not try instead to produce *less* altogether?

Calling emissions from the steel, cement, and chemical industry hard-to-abate and unavoidable emissions creates a discursive lock-in (Buschmann & Oels, 2019) and hides other options to reduce these emissions, i.e. by shifting to different materials or reducing overall consumption and production. Drawing the picture that these emissions are unavoidable depoliticizes the issue, leaving only one option to abate the emissions: CCS.

On top of that, the RESCUE study from 2019 by the German Environment Agency concludes that CCS is not necessary for Germany to abate the residual emissions from the cement, lime, and glass industry. A prerequisite, however, is that Germany manages to strengthen its natural carbon sinks. They write that "[w]ith the renunciation of the energetic use of forest residues, with the land released by not cultivating biomass for energy use, with the agricultural land released by reducing the number of livestock, the natural carbon sink is strengthened in addition to a strengthened forest management" (Purr et al., 2019, p. 32, translation by the author). In the course of the report, they explicitly say that CCS is not needed: "Thus, achieving national greenhouse gas neutrality does not require CCS, but rather the strengthening of natural sinks. At the same time, synergies can be developed with other environmental challenges, such as biodiversity protection" (Purr et al., 2019, p. 32, translation by the author). It becomes clear that to strengthen natural sinks, societal change is required. One example is that their scenario only works if Germany reduces its livestock production, i.e., if Germans reduce their meat consumption.

This goes to show that firstly, not all emissions in so-called hard-to-abate sectors are unavoidable, and secondly, that even if there remain some residual emissions from the industry, using CCS is not unavoidable either, if we are ready to change production, consumption, and land-use patterns.

6.3 Carbon lock-in and mitigation deterrence

Another important question to discuss is how carbon lock-in relates to the problem of mitigation deterrence. The concept of mitigation deterrence is mostly studied in connection with carbon dioxide removal (CDR) techniques (McLaren, 2016, 2020). While CCS at fossil power plants or industrial plants is not a CDR technique, I think that it has the potential to lead to mitigation deterrence as well. Furthermore, while I think that the concepts of mitigation deterrence and carbon lock-in are closely interlinked, they are seldom discussed together in the scientific literature.

One definition for mitigation deterrence is the following: "Mitigation deterrence can be defined as the prospect of reduced or delayed at-source reductions resulting from the introduction or consideration of another climate intervention" (McLaren, 2020, pp. 2412–2413). Reduced or delayed at-source emission reductions are mentioned multiple times in my results. Firstly, I want to point out again that RWE and Equinor plan to build new fossil gas power plants, with the prospects of the fossil gas being replaced by hydrogen sometime in the future. This clearly deters climate change mitigation, as the investments in this infrastructure could have also been made into infrastructure for renewables. When asking my interviewee at Equinor how much of their total investments go into renewable energy compared to CCS- and blue hydrogen projects, they said that they have one combined pot of money for their renewable and low carbon ambition (Interview Equinor, 2023). This shows that they treat renewable and so-called decarbonized fossil energy sources as substitutes. Hence, the higher their investments in decarbonizing fossil energy sources, the lower their investments in renewables. Further, as shown in chapter 5.3.4 Equinor is clearly using CCS to get the most out of their remaining fossil assets.

In Germany, the situation is different as there are no gas or oil fields, and as the phase-out of coal is decided. Nevertheless, as shown in Chapter 5.2, my interviewee at the BMWK did not exclude the application of CCS at fossil power plants in Germany. Although it is not the priority now, it is in the back of their minds when creating the CCS infrastructure. In addition, the promise for green hydrogen to replace blue hydrogen in the future seems empty or at least holds the risk of being broken. As my results show, neither the German government nor the companies that run concrete hydrogen projects provide any timeline for the phase-in of green hydrogen.

Overall, my results show how CCS and blue hydrogen lead to a carbon lock-in and thus create systemic barriers to decarbonization. As just explained, this leads to the risk of mitigation deterrence, because reliable climate change mitigation, i.e., reducing greenhouse gas emissions, is partly replaced by so-called carbon management. Thus, I believe that mitigation deterrence is a natural and unavoidable outcome of carbon lock-in.

6.4 Negative externalities of fossil fuel use

Opening the door for continued fossil power generation or for producing blue hydrogen in Germany further creates negative externalities tied to the use of fossil fuels. Through the coal phase-out, Germany does not have its own fossil resources anymore, which is why continuous fossil fuel use is inextricably tied to questions of energy imports and energy dependence. Norway is not the only country that exports fossil gas to Germany. Particularly through the new liquified natural gas (LNG) infrastructure in Germany, fossil gas is imported from other countries, such as the U.S.A. (Sabin, 2023). A major problem with LNG imports from the U.S.A. is that they practice fracking, a procedure that releases emissions and causes severe environmental damage (Hesselin & Lerch, 2023; Heynen, 2022). One of the companies that signed a contract for gas imports with the U.S.A. is RWE – the same company that is planning to build new fossil gas-fired power plants in Germany (Sabin, 2023).

Fracking is forbidden in Germany, but through imports, fracked gas finds a loophole into the German energy mix.

Other partners for LNG imports in Germany are Algeria, Nigeria, the Arab Emirates, and Oman (Sabin, 2023). This raises questions about energy dependence and human rights. Through the Russian war against Ukraine, Germany had to learn the hard way that being dependent on energy imports from authoritarian states is risky. Furthermore, on top of ethical considerations when importing fossil fuels from authoritarian regimes, the situation with Russia also showed how this can lead to severe problems with regard to energy security. Thus, a lock-in in fossil infrastructure is particularly problematic in Germany, not only in terms of environmental protection but also in terms of energy security.

All these problems with regard to fossil fuel use are being ignored as we reduce the issue of fossil fuel use to questions about emissions. Additional problems when using fossil resources are made invisible as CCS labels fossil fuels “carbon-neutral” and creates the image of “clean” fossil fuels. As my results show, Equinor is following this exact narrative, with my interviewee saying that once they have a CO2 solution, they don’t see any reason for stopping to use fossil resources.

7 Conclusion

In this thesis, I set out to answer in what way the German-Norwegian CCS- and hydrogen cooperation creates a carbon lock-in in Germany. As shown in my results chapter, the cooperation and specific projects related to it create infrastructural and technological, as well as institutional lock-in mechanisms. The technological and infrastructural lock-in manifests itself through the long life- and lead time of new and existing infrastructure, through its partial asset specificity, through infrastructural network effects, and through the risk of stranded assets due to the high investments in that infrastructure. The institutional lock-in comes about as Germany is revisiting its regulatory and legal framework with regard to CCS, working on a carbon management strategy that is expected to facilitate the transportation and storage of CO2 in Germany. Further, institutional lock-in is intensified through the network of powerful incumbent actors, involving both political decision-makers, as well as representatives from the fossil industry.

Based on this thesis, some options for further research come up. Firstly, an analysis of discursive lock-in mechanisms could be particularly interesting with regard to the theme of hard-to-abate sectors, as outlined above. Hence, future research could analyze the German-Norwegian partnership, with discourse as an important, and perhaps underlying, pillar of the lock-in mechanisms identified in this thesis. Secondly, the thesis is written before the publication of both the new German Carbon

Management Strategy, as well as the feasibility study by DENA and Gassco. Future research could thus complement this thesis by analyzing both documents once published. Thirdly, it would be very interesting to look at how public opinion on CCS in Germany might have changed over the past decade. Since public resistance was often mentioned as an important blocker to CCS policies and projects in Germany in the past, one can assume that public opinion might be important to determine the success of the new projects presented in this thesis. As this thesis analyzed concrete plans and policies with regard to CCS, I did not collect much material from organizations or people that are critical of CCS. Also, for my interviews, I only talked to those who are already involved with CCS and thus promote the technology. It would therefore be interesting to also study the other side of the coin, i.e., actors in Germany that are trying not to build their production on CCS and blue hydrogen but who are trying to find other solutions to reduce emissions and escape a carbon lock-in.

Finally, this thesis shows how the fight against climate change is still competing with the powerful interests of incumbent actors, notably the fossil industry. CCS is a solution to climate change for those who are trying to uphold an unsustainable status quo and who fear the solutions that tackle the roots of the problem. Therefore, CCS and other technological solutions to climate change must always be considered with care, and underlying political and economic interests and power structures must be identified. To conclude, I do not disagree when Minister Robert Habeck says, “better to put CO2 in the ground than in the atmosphere”. But this statement is misleading and disregards a third option: Leave fossil resources in the ground in the first place.

8 Bibliography

AHK. (2022, September 22). *Politik und Industrie sind sich einig: Die Deutsch-Norwegische Energiezusammenarbeit soll vertieft werden*. https://handelskammer.blog/politik-und-industrie-sind-sich-einig-die-deutsch-norwegische-energiezusammenarbeit-soll-vertieft-werden/

Anderson, S., & Newell, R. (2004). Prospects for Carbon Capture and Storage Technologies. *Annual Review of Environment and Resources*, *29*(1), 109–142. https://doi.org/10.1146/annurev.energy.29.082703.145619

Asayama, S. (2021). The Oxymoron of Carbon Dioxide Removal: Escaping Carbon Lock-In and yet Perpetuating the Fossil Status Quo? *Frontiers in Climate*, *3*. https://www.frontiersin.org/articles/10.3389/fclim.2021.673515

Bäckstrand, K., Meadowcroft, J., & Oppenheimer, M. (2011). The politics and policy of carbon capture and storage: Framing an emergent technology. *Global Environmental Change*, *21*, 275–281. https://doi.org/10.1016/j.gloenvcha.2011.03.008

Bellona Europe. (2023, January 6). *German minister Habeck's visit to Norway: Joint plan for a climate-neutral future*. Bellona.Org. https://bellona.org/news/energy-systems/hydrogen-production/2023-01-german-minister-habecks-visit-to-norway-joint-plan-for-a-climate-neutral-future

Brauers, H., Braunger, I., & Jewell, J. (2021). Liquefied natural gas expansion plans in Germany: The risk of gas lock-in under energy transitions. *Energy Research & Social Science*, *76*, 102059. https://doi.org/10.1016/j.erss.2021.102059

Bryman, A. (2012). *Social Research Methods* (Fourth Edition). Oxford University Press.

Buck, H. J. (2021). Social science for the next decade of carbon capture and storage. *Electricity Journal*, *34*(7). https://doi.org/10.1016/j.tej.2021.107003

Bui, M., Adjiman, C. S., Bardow, A., Anthony, E. J., Boston, A., Brown, S., Fennell, P. S., Fuss, S., Galindo, A., Hackett, L. A., Hallett, J. P., Herzog, H. J., Jackson, G., Kemper, J., Krevor, S., Maitland, G. C., Matuszewski, M., Metcalfe, I. S., Petit, C., … Mac Dowell, N. (2018). Carbon capture and storage (CCS): The way forward. *Energy and Environmental Science*, *11*(5), 1062–1176. https://doi.org/10.1039/c7ee02342a

Bundesministerium für Wirtschaft und Klimaschutz. (2022a). *Bundeskabinett beschließt Evaluierungsbericht zum Kohlendioxid-Speicherungsgesetz (KSpG)*. Bundesministerium für Wirtschaft und Klimaschutz. https://www.bmwk.de/Redaktion/DE/Pressemitteilungen/2022/12/20221221-bundeskabinett-beschliesst-evaluierungsbericht-zum-kohlendioxid-speicherungsgesetz-kspg.html

Bundesministerium für Wirtschaft und Klimaschutz. (2022b). *Evaluierungsbericht der Bundesregierung zum Kohlendioxid-Speicherungsgesetz (KSpG)*.

Buschmann, P., & Oels, A. (2019). The overlooked role of discourse in breaking carbon lock-in: The case of the German energy transition. *WIREs Climate Change*, *10*(3), e574. https://doi.org/10.1002/wcc.574

Cairns, R. C. (2014). Climate geoengineering: Issues of path-dependence and socio-technical lock-in. *WIREs Climate Change*, *5*(5), 649–661. https://doi.org/10.1002/wcc.296

Carton, W., Asiyanbi, A., Beck, S., Buck, H. J., & Lund, J. F. (2020). Negative emissions and the long history of carbon removal. *WIREs Climate Change*, *11*(6), e671. https://doi.org/10.1002/wcc.671

Deutsche Energie-Agentur GmbH. (2021). *Dena-Leitstudie Aufbruch Klimaneutralität*.

Deutsches GeoForschungsZentrum, S. 6 3: G. S. (2018). *Schlussbericht Projekt COMPLETE - Forschungsprojekt COMPLETE, Pilotstandort Ketzin - Erstmaliger Abschluss des kompletten Lebenszyklus eines CO2-Speichers im Pilotmaßstab mit Schwerpunkt auf Überwachung bei Stilllegung (CO2 post-injection monitoring and post-closure phase at the Ketzin pilot site), Sonderprogramm Geotechnologien: Berichtszeitraum: 01.01.2014-31.12.2017*. https://doi.org/10.2314/GBV:1028936389 dpa. (2012, June 28). Einigung zur CCS-Technologie: Schleswig-Holstein nicht unterkellern. *taz*. https://taz.de/!5090300/

Equinor. (2022, August 30). *Equinor and Wintershall Dea partner up for large-scale CCS value chain in the North Sea*. https://www.equinor.com/news/20220830-equinor-wintershall-dea-large-scale-ccs-value-chain

Equinor. (2023, January 5). *Equinor and German energy major RWE to cooperate on energy security and decarbonization*. https://www.equinor.com/news/20230105-equinor-rwe-cooperation

Erickson, P., Kartha, S., Lazarus, M., & Tempest, K. (2015). Assessing carbon lock-in. *Environmental Research Letters*, *10*(8), 084023. https://doi.org/10.1088/1748-9326/10/8/084023

Hesselin, C., & Lerch, I. (2023, April 28). *LNG: Wie viel Flüssigerdgas kommt derzeit in Deutschland an?* https://www.ndr.de/nachrichten/info/LNG-Wie-viel-Fluessigerdgas-kommt-derzeit-in-Deutschland-an,lng632.html

Heynen, M. (2022, May 6). Fracking: Warum Fracking in Deutschland keine Option ist. *Die Zeit*. https://www.zeit.de/wissen/umwelt/2022-05/fracking-erdgasfoerderung-klimaschutz-klimaziele?utm_referrer=https%3A%2F%2Fwww.google.com%2F

Iberdrola. (2023). *Difference between green and blue hydrogen*. Iberdrola. https://www.iberdrola.com/about-us/what-we-do/green-hydrogen/difference-hydrogen-green-blue

International Energy Agency. (2021). *Net Zero by 2050—A Roadmap for the Global Energy Sector*.

IPCC. (2005). *Carbon Dioxide Capture and Storage* (p. 481). Cambridge University Press. https://www.ipcc.ch/report/carbon-dioxide-capture-and-storage/

IPCC. (2022). Summary for Policymakers. In P. R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, & J. Malley (Eds.), *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Isella, A., & Manca, D. (2022). GHG Emissions by (Petro)Chemical Processes and Decarbonization Priorities—A Review. *Energies*, *15*(20), Article 20. https://doi.org/10.3390/en15207560

Janipour, Z., Swennenhuis, F., de Gooyert, V., & de Coninck, H. (2021). Understanding contrasting narratives on carbon dioxide capture and storage for Dutch industry using system dynamics. *International Journal of Greenhouse Gas Control*, *105*. https://doi.org/10.1016/j.ijggc.2020.103235

Jayanti, S. E.-P. (2022). Repurposing pipelines for hydrogen: Legal and policy considerations. *Energy Reports*, *8*, 815–820. https://doi.org/10.1016/j.egyr.2022.11.063

Kates, R. W., Clark, W. C., Corell, R., Hall, J. M., Jaeger, C. C., Lowe, I., McCarthy, J. J., Schellnhuber, H. J., Bolin, B., Dickson, N. M., Faucheux, S., Gallopin, G. C., Grübler, A., Huntley, B., Jäger, J., Jodha, N. S., Kasperson, R. E., Mabogunje, A., Matson, P., … Svedin, U. (2001). Sustainability Science. *Science*, *292*(5517), 641–642. https://doi.org/10.1126/science.1059386

Lefvert, A., Rodriguez, E., Fridahl, M., Grönkvist, S., Haikola, S., & Hansson, A. (2022). What are the potential paths for carbon capture and storage in Sweden? A multi-level assessment of historical and current developments. *Energy Research & Social Science*, *87*, 102452. https://doi.org/10.1016/j.erss.2021.102452

LobbyControl. (2021, March 24). *Klimaforschung: Studie der Bundesregierung gekapert von der Gaslobby?* LobbyControl. https://www.lobbycontrol.de/lobbyismus-und-klima/klimaforschung-studie-der-bundesregierung-gekapert-von-der-gaslobby-86409/

London Protocol, (2006). https://www.epa.gov/sites/default/files/2015-10/documents/lpamended2006.pdf

Lopez, G., Galimova, T., Fasihi, M., Bogdanov, D., & Breyer, C. (2023). Towards defossilised steel: Supply chain options for a green European steel industry. *Energy*, *273*. https://doi.org/10.1016/j.energy.2023.127236

Ma, J., Li, L., Wang, H., Du, Y., Ma, J., Zhang, X., & Wang, Z. (2022). Carbon Capture and Storage: History and the Road Ahead. *Engineering*, *14*, 33–43. https://doi.org/10.1016/j.eng.2021.11.024

Markusson, N., & Haszeldine, S. (2009). ‘Capture readiness’–lock-in problems for CCS governance. *Energy Procedia*, *1*(1), 4625–4632. https://doi.org/10.1016/j.egypro.2009.02.284

Martin-Roberts, E., Scott, V., Flude, S., Johnson, G., Haszeldine, R. S., & Gilfillan, S. (2021). Carbon capture and storage at the end of a lost decade. *One Earth*, *4*(11), 1569–1584. https://doi.org/10.1016/j.oneear.2021.10.002

Müller, N., Herz, G., Reichelt, E., Jahn, M., & Michaelis, A. (2021). Assessment of fossil-free steelmaking based on direct reduction applying high-temperature electrolysis. *Cleaner Engineering and Technology*, *4*, 100158. https://doi.org/10.1016/j.clet.2021.100158

OECD. (2016). *20 Years of Carbon Capture and Storage: Accelerating Future Deployment*. Organisation for Economic Co-operation and Development. https://www.oecd-ilibrary.org/energy/20-years-of-carbon-capture-and-storage_9789264267800-en

Office of the Prime Minister, & Ministry of Petroleum and Energy. (2023, January 5). *Joint Statement—Germany – Norway—Hydrogen*. Government.No. https://www.regjeringen.no/en/whatsnew/dep/smk/press-releases/2023/closer-cooperation-between-norway-and-germany-to-develop-green-industry/joint-statement-germany-norway-hydrogen/id2958105/

Office of the Prime Minister & Ministry of Trade, Industry and Fisheries. (2023, January 5). *Joint Declaration—German-Norwegian Partnership on Climate, Renewable Energy and Green Industry*. Government.No. https://www.regjeringen.no/en/whatsnew/dep/smk/press-releases/2023/closer-cooperation-between-norway-and-germany-to-develop-green-industry/joint-declaration-german-norwegian-partnership-on-climate-renewable-energy-and-green-industry/id2958104/

OGE. (2023a). *H2morrow—Act today to be greenhouse gas neutral by 2050*. OGE. https://oge.net/en/sustainable/projects/our-hydrogen-projects/h2morrow

OGE. (2023b). *Join OGE on the path to climate neutrality!* OGE. https://co2-netz.de/en

Öhman, A., Karakaya, E., & Urban, F. (2022). Enabling the transition to a fossil-free steel sector: The conditions for technology transfer for hydrogen-based steelmaking in Europe. *Energy Research & Social Science*, *84*, 102384. https://doi.org/10.1016/j.erss.2021.102384

Otto, A., Robinius, M., Grube, T., Schiebahn, S., Praktiknjo, A., & Stolten, D. (2017). Power-to-Steel: Reducing CO2 through the Integration of Renewable Energy and Hydrogen into the German Steel Industry. *Energies*, *10*(4), Article 4. https://doi.org/10.3390/en10040451

Paltsev, S., Morris, J., Kheshgi, H., & Herzog, H. (2021). Hard-to-Abate Sectors: The role of industrial carbon capture and storage (CCS) in emission mitigation. *Applied Energy*, *300*, 117322. https://doi.org/10.1016/j.apenergy.2021.117322

Parson, E. A., & Buck, H. J. (2020). Large-scale carbon dioxide removal: The problem of phasedown. *Global Environmental Politics*, *20*(3), 70–92. Scopus. https://doi.org/10.1162/glep_a_00575

Pekic, S. (2022, August 4). Wintershall Dea and NWO to work on BlueHyNow hydrogen production plant. *Offshore Energy*. https://www.offshore-energy.biz/wintershall-dea-and-nwo-to-work-on-bluehynow-hydrogen-production-plant/

Pimm, A. J., Cockerill, T. T., & Gale, W. F. (2021). Energy system requirements of fossil-free steelmaking using hydrogen direct reduction. *Journal of Cleaner Production*, *312*, 127665. https://doi.org/10.1016/j.jclepro.2021.127665

Purr, K., Günther, J., Lehmann, H., & Nuss, P. (2019). *Wege in eine ressourcenschonende Treibhausgasneutralität – RESCUE: Langfassung*. Umweltbundesamt. https://www.umweltbundesamt.de/rescue

Qureshi, H. J., Ahmad, J., Majdi, A., Saleem, M. U., Al Fuhaid, A. F., & Arifuzzaman, M. (2022). A Study on Sustainable Concrete with Partial Substitution of Cement with Red Mud: A Review. *Materials*, *15*(21), Article 21. https://doi.org/10.3390/ma15217761

Rumayor, M., Fernández-González, J., Domínguez-Ramos, A., & Irabien, A. (2022). Deep Decarbonization of the Cement Sector: A Prospective Environmental Assessment of CO2 Recycling to Methanol. *ACS Sustainable Chemistry and Engineering*, *10*(1), 267–278. https://doi.org/10.1021/acssuschemeng.1c06118

Sabin, F. (2023, January 24). *LNG kettet Europa und Deutschland in Gas-Fragen an die USA*. FOCUS online. https://www.focus.de/finanzen/news/lng-abhaengigkeit-auf-jahrzehnte-lng-kettet-europa-und-deutschland-in-gas-fragen-an-die-usa_id_182667630.html

Sandberg, E., & Krook-Riekkola, A. (2022). The impact of technology availability on the transition to net-zero industry in Sweden. *Journal of Cleaner Production*, *363*. Scopus. https://doi.org/10.1016/j.jclepro.2022.132594

Scott, V., & Geden, O. (2018). The challenge of carbon dioxide removal for EU policy-making. *Nature Energy*, *3*(5), Article 5. https://doi.org/10.1038/s41560-018-0124-1

Sekera, J., & Lichtenberger, A. (2020). Assessing Carbon Capture: Public Policy, Science, and Societal Need. *Biophysical Economics and Sustainability*, *5*(3), 14. https://doi.org/10.1007/s41247-020-00080-5

Seto, K. C., Davis, S. J., Mitchell, R. B., Stokes, E. C., Unruh, G., & Ürge-Vorsatz, D. (2016). Carbon Lock-In: Types, Causes, and Policy Implications. *Annual Review of Environment and Resources*, *41*(1), 425–452. https://doi.org/10.1146/annurev-environ-110615-085934

Shackley, S., & Thompson, M. (2012). Lost in the mix: Will the technologies of carbon dioxide capture and storage provide us with a breathing space as we strive to make the transition from fossil fuels to renewables? *Climatic Change*, *110*(1–2), 101–121. Scopus. https://doi.org/10.1007/s10584-011-0071-3

Umweltbundesamt. (2022, May 23). *Carbon Capture and Storage*. Umweltbundesamt. https://www.umweltbundesamt.de/themen/wasser/gewaesser/grundwasser/nutzung-belastungen/carbon-capture-storage

Unruh, G. C. (2000). Understanding carbon lock-in. *Energy Policy*, *28*(12), 817–830. https://doi.org/10.1016/S0301-4215(00)00070-7

Vallentin, D. C. (2022, September 15). CO_2-Speicherung: Wird Deutschland so klimaneutral? *Die Zeit*. https://www.zeit.de/wissen/2022-09/co2-speicherung-ccs-norwegen-deutschland

Vergragt, P. J. (2012). Carbon capture and storage: Sustainable solution or reinforced carbon lock-in? In *Governing the Energy Transition: Reality, Illusion or Necessity?* (pp. 101–124). https://doi.org/10.4324/9780203126523

Vergragt, P. J., Markusson, N., & Karlsson, H. (2011). Carbon capture and storage, bio-energy with carbon capture and storage, and the escape from the fossil-fuel lock-in. *Global Environmental Change*, *21*(2), 282–292. https://doi.org/10.1016/j.gloenvcha.2011.01.020

Vijayan, D. S., Dineshkumar, Arvindan, S., & Shreelakshmi Janarthanan, T. (2020). Evaluation of ferrock: A greener substitute to cement. *Materials Today: Proceedings*, *22*, 781–787. https://doi.org/10.1016/j.matpr.2019.10.147

Vogl, V., Åhman, M., & Nilsson, L. J. (2018). Assessment of hydrogen direct reduction for fossil-free steelmaking. *Journal of Cleaner Production*, *203*, 736–745. https://doi.org/10.1016/j.jclepro.2018.08.279

Wehrmann, B. (2022, August 16). *Norway agrees to sustain maximum gas deliveries to Germany*. Clean Energy Wire. https://www.cleanenergywire.org/news/norway-agrees-sustain-maximum-gas-deliveries-germany

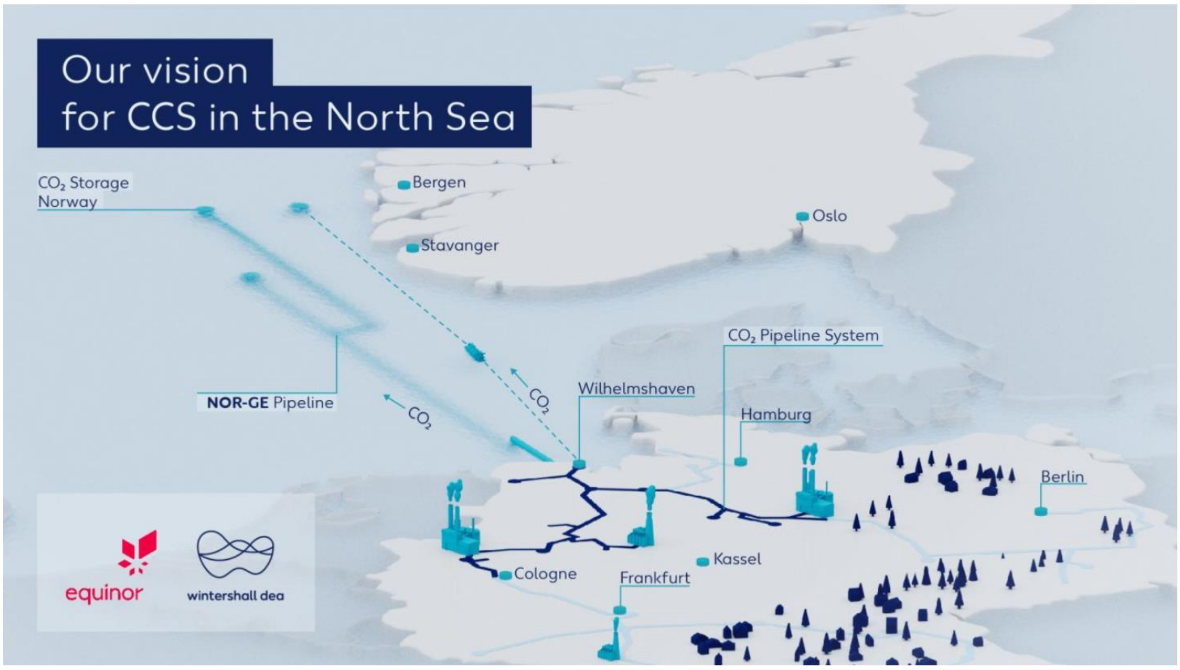
9 Appendix

Appendix A: Illustration of the partnership between Equinor and RWE

Illustration of the partnership between Equinor and RWE on a hydrogen value chain between Germany and Norway (Equinor, 2023).

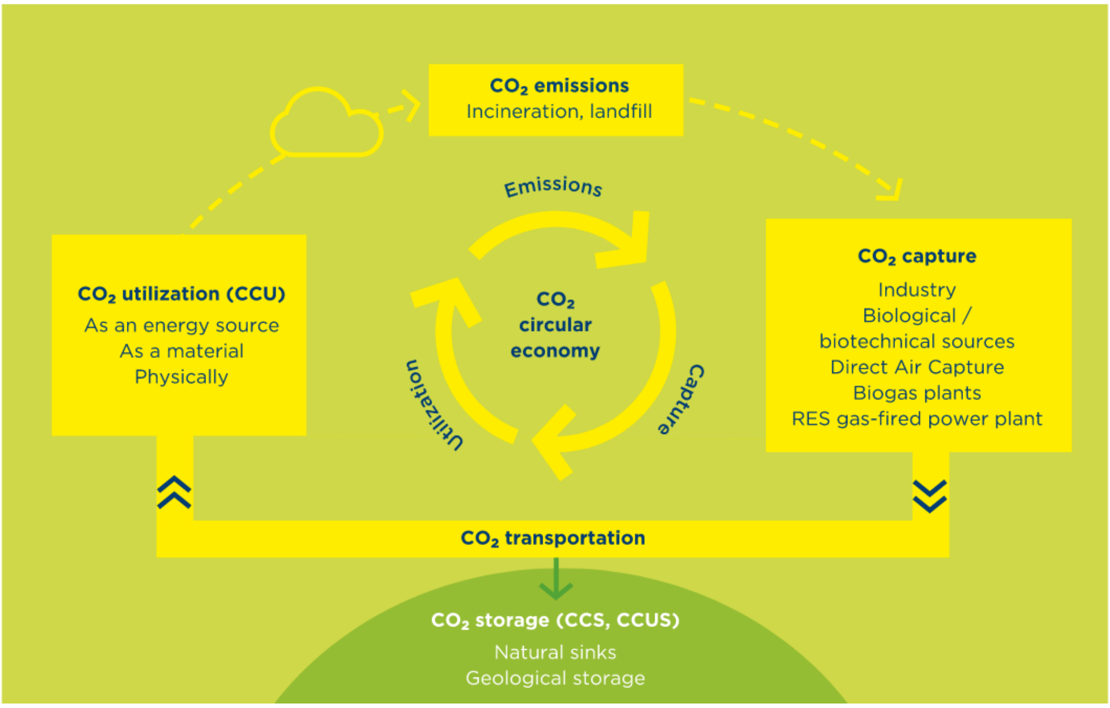
Appendix B: Illustration of the partnership between Equinor and Wintershall Dea

Illustration of the partnership between Equinor and Wintershall Dea on a CO2 pipeline from Germany to Norway (Equinor, 2022).



Appendix C: Illustration of OGE’s CO2 circular economy

Illustration of OGE's CO2 circular economy (OGE, 2023b).



Appendix D: Different processes of green and blue hydrogen production

Illustration of the different processes of green and blue hydrogen production (Iberdrola, 2023).