Developing value chains for CO_2 storage and blue hydrogen in Europe (Device)

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1 Excellence

1.1 State of the art, knowledge needs and project objectives

While prominent international organizations like the IEA and the IPCC have argued that Carbon Capture and Storage (CCS) is pivotal in ensuring a cost-efficient solution to the climate change problem, to date there is no market for CO_2 storage. A variety of firms that currently emit CO_2 may in the future invest in carbon capture and thus demand CO_2 storage services. Likewise, fossil-fuel based hydrogen production combined with carbon capture will also demand storage of the removed CO_2. This research project investigates how to develop robust value chains for *both* CO_2 storage and fossil-based hydrogen with CCS, and examines policy implications of their interlinkages.

Barriers to developing value chains for CO_2 storage and hydrogen. First, there is *no commercial market for CO_2 storage*. Whereas international bodies like the IEA, the IPCC and the EU Commission have argued that CCS should play an important role in the decarbonization of the electricity sector and also in some manufacturing sectors, there is a huge gap between what is considered to be the cost efficient path of deployment of CCS and actual CCS capacity. For example, according to the IEA's Sustainable Development Scenario, see IEA (2018), the cost-efficient global capture capacities in the power and manufacturing sector in 2030 are 350 million ton and 500 million ton (Mt) of CO_2, respectively, yet the current capacities are around 3 Mt and 30 Mt of CO_2. Hence, the current potential demand for storage is marginal, whereas the future potential can be substantial.

Second, there is *no significant commercial market for hydrogen* in Europe. Currently, hydrogen is a marginal energy carrier in Europe. Its share of the European energy mix is less than 2%. Hydrogen is mainly used by refineries and by the chemical industry to produce ammonia. Yet, hydrogen has a great potential. In the manufacturing industries, it can be used to produce methanol and steel. In transport, it can be used for heavy-duty road vehicles, to power maritime transport, and maybe even for aviation in the long run. In the building sector, hydrogen can be used for heating and cooking by replacing natural gas. In the electricity sector, hydrogen can be used to store energy. To increase the take-up of hydrogen radically, an infrastructure for transport is needed, for example, by utilizing parts of the existing gas transmission and distribution grids. Also, potential users of hydrogen must find it interesting switching to hydrogen. This requires, among other things, that the price of hydrogen is not prohibitively high.

Hydrogen faces, however, *high costs.* According to European Commission (2020a), the cost of "blue" hydrogen, i.e., hydrogen produced from fossil fuels and combined with CCS, is about one third higher than the cost of conventional ("grey") hydrogen (prior to paying for CO_2 emissions). For green hydrogen, i.e., hydrogen produced through electrolysis of water powered by renewable electricity, the corresponding number is at least two, maybe even higher than three. Furthermore, even grey hydrogen is expensive, partly because of high energy loss factors, see IRENA (2000).

Challenges to developing value chains for CO_2 and hydrogen. To develop markets for both CO_2 and hydrogen, a classical *coordination problem* has to be overcome: A blue hydrogen producer may not be willing to invest in facilities prior to having a reliable solution for storage of CO_2. Likewise, an actor considering to develop a storage site may not be willing to invest before being confident that there are clients with captured CO_2 demanding CO_2 storage. For blue hydrogen producers, the coordination problem is double sided: the potential producer of blue hydrogen may not be willing to invest before knowing that there will also be demand for hydrogen.

Economic theory suggests that the coordination problem rationalizes government policy, for example, temporary support schemes to ensure that a socially warranted outcome is realized. Without policy support, a market may never materialize, or investment may be radically lower than what is socially optimal. Hence, there may be more than one outcome of the coordination game, and thus the objective of the government (e.g., the EU) should be to ensure that the socially preferable outcome is realized. Note, however, that the Norwegian government has solved the coordination problem for one specific storage site by launching the Northern Lights project (see below). Yet, for other countries, as well as for expansion of the Norwegian storage capacity, the actors face a coordination problem.

Second, development of a value chain requires suitable *business models* on how risks should be shared between key actors. The government could offer risk sharing schemes to ensure socially right incentives for private actors to invest, i.e., provide incentives that sustain socially warranted investment in the various parts of a value chain. For example, the government could hedge private investment in carbon capture by guaranteeing a maximum price for transportation and storage services.

The Norwegian Langskip project, which was approved by the Norwegian parliament in 2020 (OED, 2020), is an interesting example of risk sharing. The project encompasses the Northern Lights project, as well as investment in capture facilities at Norcem (cement manufacturer) and possibly at Fortum Oslo Varme (transforming non-recyclable waste to energy), and aims at developing a full-scale CCS value chain in Norway (by 2024).

Total costs of the Langskip project have been estimated to 25 billion NOK, see OED (2020), of which the Norwegian government will cover almost 70%. The key elements in the Northern Lights project is a pipe from the Western coast of Norway to an offshore storage site. In the first phase of the project, the annual CO_2 terminal capacity and the annual injection capacity to the storage is 1.5 Mt of CO_2. However, in phase two the latter two capacities can be expanded to 5 Mt of CO_2. Equinor has worked out scenarios for annual injection to storage on the Norwegian Continental Shelf at 20 Mt and even 100 Mt of CO_2 (Equinor, 2019). According to the hydrogen strategy of the Norwegian government, a CO_2 value chain is a prerequisite for production of blue hydrogen, see OED and KMD (2020). Currently, Northern Lights is the only approved CO_2 storage project in Europe, but storage facilities in the Netherlands and the UK may materialize in the future. Such projects may have profound impacts on the profitability of CO_2 value chains.

Finally, there must be demand for CO_2 storage services. This requires that policy makers and economic actors have *confidence in a CO_2 value*. In particular, actors must believe that transportation and storage facilities are available when needed, and that there will be no leakage from stored CO_2. These concerns may undermine investments in the CO_2 value chain. However, once actors experience that the CO_2 value chain works, investment may take off. Again, there might be a role for public policy.

Structure of work packages (WPs). In work package 1, we study the extent to which and how different types of social acceptance and economic factors influences industry demand for CO_2 storage supplied by Northern Lights in key European countries, and how learning, for example, about the risk of leakage from CO_2 storage, may affect social acceptance and in turn industry demand, see Figure 1. WP 2 focuses on supply of CO_2 storage from competing storage actors, all enjoying economies of scale and all being capable of obtaining positive learning effects from industrial projects.

Typically, development of value chains involves both private actors and the government. In WP 3, we examine risk sharing schemes between the private and public sector, i.e., business models, from an economic and legal perspective. The purpose is to identify government support schemes that provide incentives for private investment in the different parts of the CO_2 value chain and the hydrogen value chain that are socially warranted. Finally, in WP 4 we study jointly the CO_2 value chain and the hydrogen value chain, using information from the previous WPs, i.e., demand structure for CO_2 storage, supply of CO_2 storage (in particular, the importance of Northern Lights), and business models for various parts of the two value chains, see Figure 1. In WP 4, we examine how government policy may ensure the development of these two value chains. In addition, we discuss, and illustrate numerically, how EU targets for hydrogen production impact blue hydrogen production and the components in the CO_2 value chain. New markets and new value chains require new standards and new regulations. In WP 4, we therefore also discuss optimal architecture of the legislation on hydrogen. Note that there are no interdependencies between the WPs.

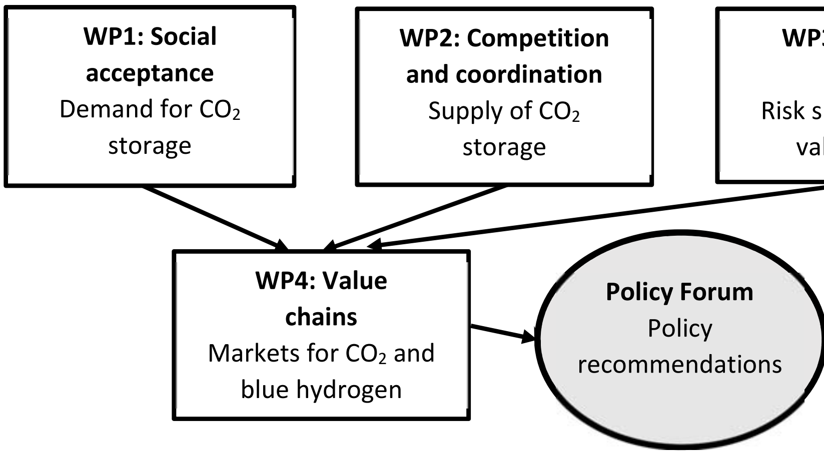

Figure 1 Work packages

Knowledge gaps. First, there is an extensive literature on deployment of carbon capture technologies, in the European electricity sector (Golombek et al. 2011), in the European manufacturing sector (Oei et al. 2016), and in the global energy system (van Vuuren et al. 2019). This literature simply assumes that the coordination problem is solved; the level of activity in transportation and storage of CO2 follows from demand for these services when actors face fixed unit costs of transportation and storage. In economics, the literature on the coordination problem goes back to Farrell and Saloner (1986). This line of research was followed up by Chou and Shy (1990) and Heggedahl and Greaker (2010). Our own study of the CCS value chain, Golombek et al. (2021), builds on this literature, and is, to the best of our knowledge, the only academic study of the CCS value chain taking the coordination problem into account. Furthermore, we are not aware of any academic study on the hydrogen value chain. In particular, there is a substantial knowledge gap on how the government should ensure value chains for both CO2 and hydrogen.

Second, acceptance of CCS is one barrier to establishing a value chain for CO_2. While research on CCS and acceptance has been conducted, the recent developments in CCS projects in Netherlands, the UK and Norway, as well as with the London protocol amendment in 2019 that facilitates cross-border transportation of CO_2 suggest that the topic is understudied. In addition, the mechanisms on how political framework conditions are influenced by social acceptance need refinements (Dermont et al., 2017).

The primary objective of this project is to study how social acceptance, government policy and regulations, and new business models can sustain the development of efficient value chains for hydrogen and captured CO_2 in Europe.

1.2 Research questions and hypotheses, theoretical approach and methodology

WP 1 Social acceptance and demand for CO_2 storage (FC, FNI, NMBU)

T 1.1: *Examine how and the extent to which social acceptance influence industry demand for CO_2 storage supplied by Northern Lights in key European countries*

T 1.2: *Study how industry demand for storage can evolve over time*

Task 1.1 Social acceptance and industry demand for storage of CO_2

We will study how social acceptance and economic factors affect *industry demand* for CO_2 storage, offered by Northern Lights.

The literature highlights different types of social acceptance, in particular, public acceptance and political acceptance (Wolsink, 2020). Our basic expectation for *public acceptance* is that within and across the case countries (see below), acceptance of offshore CO_2 storage in Norway will be greater than acceptance of domestic storage. This is because domestic storage has been the most controversial part of CCS in key European countries (Inderberg and Wettestad, 2015). We will map public acceptance in each case country by examining secondary sources such as public reports, existing polls and media articles as well as through expert interviews.

The second explanatory factor is *political acceptance*, which, seen as general perception of a technology, is regarded as critical for establishing a large market for CO_2 storage (Wüstenhagen et al., 2007). As an operational measure of political acceptance, we will examine political framework conditions for catching and transporting CO_2 in each case country, with a particular focus on barriers and opportunities for industry participation in the Northern Lights project. Such political conditions include support policies for carbon capture, pilot support, environmental standards, and other legal requirements. The basic expectation is that the more facilitative the political framework conditions are, the greater the industry demand for CO_2 transportation and storage.

A third set of explanatory factors is *access* to and *cost* of using the transportation and storage services as well as the perceived success of *demonstration projects*. A straightforward expectation is that free access and low cost of using the infrastructure as well as successful demonstration will increase industry demand.

The case countries are Germany, the Netherlands, and the UK, which are expected to be important customers for the Northern Lights project. The analysis will build on documentary analysis of laws and regulations, industry support and R&D policy, official strategies and goals of relevance to carbon capture in the case countries. For the market actors, we will study annual reports from a selection of the most likely industries that may become clients of the Northern Lights. We will use qualitative data coding tools like NVivo to code text to ensure systematic management of the document information. The document analyses will be supplemented with selected interviews to ensure a valid interpretation of policy and that the most relevant information is included.

Task 1.2 Learning effects, evolution of social acceptance and demand for storage

In Task 1.2, we will use the qualitative inputs from Task 1.1 to study how industry demand for storage services can evolve over time. To do this, we will use evolutionary game theory (Sandholm, 2020), where learning may make agents update their strategy from one period to another based on their payoff of doing so. We will develop a model with industries that consider CCS as an option. Demand for storage will depend on several factors, confer Task 1.1. For example, if there is no leakage from storage sites over time (i.e., learning), acceptance may increase, which may again increase demand for storage.

In evolutionary games, multiple equilibria may exist. In the case of possible leakage risk, there may be one equilibrium where nobody demands storage, and one equilibrium where a large number of industries demand storage because they have learned that the probability of leakage is low. An interesting question is how to move from the low equilibrium to the high equilibrium. A shift in some variables that are crucial for the industries, for instance, political decisions, may change the dynamics, but the shift has to be large enough for industries to profoundly change their attitude to CCS. A calibration of the theory model we be undertaken to understand how policy changes may interact with social acceptance and demand for storage.

WP 2: Competition and coordination of storage for CO_2 (FC, IFE, NMBU, UiO)

T 2.1:	*Examine how a market for storage in the North Sea can emerge over time when there are competition among storage suppliers, economies of scale, as well as learning and network effects*
T 2.2:	*Ensuring good resource management through integrated planning and permitting procedures for offshore energy*

Task 2.1 A market for storage in the North Sea

As part of the Northern Lights project, Norway plans a transport pipe for CO_2 to a storage site in the North Sea. However, Scotland, Netherlands and Denmark also plan storage sites for CO_2. While they differ in size, they all have large fixed costs and will therefore be dependent on expanding their activity and attract customers to become profitable. Competition may emerge, although different geographical locations will hamper it to some degree.

In addition, there are learning effects from industrial development projects that may reduce costs, also for other storage suppliers. Furthermore, a market for transport and storage may not kick off by itself due to coordination problems: a capture facility needs access to transportation and storage at affordable costs, while storage providers need enough customers to become profitable, see the discussion in section 1.1. Thus, the market may need an initial push in order to overcome entry barriers.

In Task 2.1 we examine the optimal investment plan for storage suppliers. We will investigate what public policies that may be needed to realize a sufficiently large market for storage of CO_2 in the North Sea, given the ambitious long-term climate targets in Europe. In particular, how will Northern Lights, the first supplier of storage in Europe, affect the development of the value chain for storage? Will the approval of the Northern Lights be a game changer, i.e., lay the foundation for a comprehensive market for CO_2 storage in Europe, or is additional policy initiatives required, for example, by the EU?

We will develop a stylized two-period model that takes into account the elements described above. In the model, some agents supply and others demand storage services. In the first period, some agents may invest in capture facilities, and thereby demand storage services in the next period, while others may invest in storage sites. The outcome in the second period is, however, uncertain in the first period, because multiple equilibria are possible, for example, no one may have invested in storage facilities in the first period, except Northern Lights.

We will draw on our earlier studies using game theory applied to the gas market (e.g., Golombek et al. 1998; Gabriel et al. 2012; Massol and Banal-Estañol, 2018) and also on the literature on network effects (Greaker and Midttømme, 2016). The theory model will be calibrate on data from the North Sea area to illustrate numerically the identified effects.

Task 2.2 G*ood resource management*

Good resources management has been and remains a mantra in Norwegian petroleum policy. It is multifaceted and is reflected in many provisions of the currently applicable 1996 Petroleum Activities Act. Good resources management is also referred to by the authorities in relation to CCS because the value chains of petroleum extraction and transportation/storage of CO_2 have multiple similarities (Banet, 2021a). The similarities in the operations and the legal regimes could allow for more interaction between the two sectors (Banet, 2020).

Task 2.2 will investigate how requirements for a more integrated energy planning on the one hand, and more integrated permitting regime of offshore activities on the other hand (petroleum extraction, hydrogen production and CCS), can contribute to improved resources management offshore. We will examine the possible links to be made between legislative requirements put on licensees/operators, both in terms of exploitation of seabed reservoirs and also of marine space. The analysis will be based on i) a systematic review of the legal regimes applicable to offshore energy/petroleum resources and CO_2 storage in Norway, ii) a mapping of the possible interactions between these activities, and iii) identification of the mechanisms for promoting good resources management in the context of more integrated, low-carbon energy systems offshore. The analysis will also involve a comparative analysis of the regimes in the UK, Netherlands and Denmark, based on existing academic collaborations.

Work package 3: Business models for developing a CO_2 value chain (FC, UiO)

T 3.1: Study how the government should lower barriers to investment in the CO_2 value chain trough risk sharing with private actors

T 3.2 Assess business models from a legal perspective

A business model refers to how a value chain is organized and structured with the aim of controlling risks and optimizing value for the actors involved. To analyze business models for CCS, we will set up a framework which includes the key actors in the CO_2 value chain, their investment choices, and type of uncertainties they are exposed to: (a) an investor in a capture facility will be uncertain on the CO_2 emission price, and thus, on the amount of CO_2 expenditures that can be saved, and also uncertain on the cost of alternative technologies, e.g., a cement factory may consider to switch to bio-based coal, (b) both an actor considering investment in a capture facility and an actor considering investment in a CO_2 transport solution, that is, a specialized ship and/or a pipeline, will be uncertain about the extent to which CO_2 storage will be available to a reasonable price, and (c) an investor in CO_2 storage may be uncertain on the demand for storage services.

The government can reduce the uncertainty of the private actors by offering risk sharing schemes. We will analyze the following business models:

- A feed-in tariff for carbon capture: The government guarantees a minimum price for all captured CO_2. Without any involvement from the government, an investor in a capture facility saves the amount of CO_2 captured times an uncertain future CO_2 permit price. The government could hedge this private investment by committing to paying the firm the difference between the future permit price (which at the time of investment is uncertain) and a guaranteed price. If the guaranteed price turns out to exceed the future permit price, no transfer is obtained from the government.
- A storage guarantee: The government guarantees that it will be responsible for all captured CO_2 that is transported to a specific terminal site, decided by the government. If the government does not succeed in developing storage at this site, the government will anyway be responsible for the captured CO_2 that is delivered to the site. The scheme includes a price for storage, which will be collected by the government.
- A transport and storage guarantee: The government guarantees that it will be responsible for all captured CO_2 before it is transported to a specific terminal site. If the government fails in developing the necessary infrastructure for transportation and storage, the government will anyway be responsible for the captured CO_2. The scheme includes a price for transport and a price for storage, to be paid to the government.

For each business model, and combinations of these, we will examine their properties, in particular, the investment incentives, and compare these to how much investment, in the three parts of the CCS value chain, that should materialize from a social point of view. We will also rank the business models from the perspective of each of the three types of actors in the CCS value chain.

In addition to assess the business models with respect to economic incentives and risk sharing, we will in task 3.2 assess their legal feasibility, in particular, relative to the forthcoming new state aid rules, see O'Brien and Banet (2021) for a legal study on risk sharing in the CCS value chain.

Work package 4: The future EU markets for hydrogen and captured CO_2 (FC, IFE, UiO)

T 4.1: Identify how the EU could support hydrogen and CCS to ensure a sustainable EU energy system

T 4.2: Calibrate the theory model to identify equilibrium prices of hydrogen and storage services, and the magnitude of policy instruments necessary to support the EU hydrogen strategy.

T 4.3 Discuss suitable architecture of the legislation on hydrogen.

Tasks 4.1 and 4.2 Supporting hydrogen and CCS to ensure a sustainable EU energy system

Norway has a large potential for storing CO_2 under the sea bottom on the Norwegian Continental Shelf, confer the approved Northern Lights project. Norway also has the potential to become a large supplier of blue hydrogen to the EU by utilizing its natural gas reserves. Supply of blue hydrogen and storage of CO_2 are interlinked activities, and the potential value chains for CO_2 and hydrogen are both characterized by economies of scale. Whereas these factors point at a great potential for blue hydrogen and storage of CO_2, there will be inter-fuel competition in the EU energy markets.

Building on work packages 1, 2 and 3, work package 4 will examine the future markets for hydrogen and captured CO_2 in Europe, emphasizing the importance of the hydrogen value chain, the CCS value chain, their interlinkages, and design of policy. A theory-based simulation model will be developed that captures the main characteristics of markets for hydrogen, captured CO_2, natural gas and electricity in a consistent way. Key elements in the model are (i) production of blue hydrogen based on natural gas combined with CCS, (ii) the supply of CO_2 transport and storage services from competing actors, confer work package 2, (iii) production of green hydrogen based on renewable electricity, (iv) demand for hydrogen from end-users of hydrogen (confer work package 1) and from actors using hydrogen to store energy), (v) demand for natural gas (from blue hydrogen suppliers, end-users and gas power stations), and (vi) supply of renewable electricity and gas power to the electricity market. The model will highlight the interconnections between markets and value chains, and also the design of instruments, including the EU ETS, to achieve policy targets.

To calibrate the model, our starting point is the current activity level among end-users of fossil fuels that may consider to switch to hydrogen (industry, the building sector and transport). Building on work package 1, we will assume that a certain fraction of the energy used in these sectors is replaced by hydrogen at cost-based prices for hydrogen. This fraction will mirror the assumed EU policy that supports a market for hydrogen. For instance, the EU may seek to decarbonize transport through a zero-emission vehicle mandate.

By simulating the model, we will obtain equilibrium values for variables like blue and green hydrogen production, the use of hydrogen in various sectors, stored CO_2, as well as prices for electricity, hydrogen and storage of CO_2. The outcome will be compared to what is socially warranted, that is, what in economics is referred to as the first-best social outcome. We will examine deviations between the social optimum and the market outcome; these may reflect factors like the coordination problem/network effects, as well as economies of scale and learning effects, i.e., what is usually referred to as market imperfections in economics. To correct for the deviations, we will discuss policy measures, including risk sharing schemes (confer work package 3), that should be implemented to reach the socially optimal outcome.

As an alternative to compare the market outcome to the socially optimal outcome, we also want to examine how “strategic” hydrogen targets of the EU impact the markets when these targets are supported by policy measures. Two alternative targets that is in line with the EU hydrogen strategy, see European Commission (2020b), is i) a portfolio mandate for green hydrogen, and ii) minimum production of green hydrogen.

A portfolio mandate for green hydrogen requires that a certain share of hydrogen originates from renewable electricity. This will affect both the user price of hydrogen and the price of electricity. Because demand for electricity will increase, the use of coal and natural gas to power electricity plants might increase, even if the price of EU ETS permits increase. Minimum production of green hydrogen can be supported by subsidies to green hydrogen production, for example, a guaranteed price for hydrogen, or investment support for electrolyzers.

By simulating the model, we will find find the value of the instruments that sustain the policy goal. We can then compare the simulated outcome to the socially optimal outcome, and discuss whether additional policy instruments should be used in order to improve the market outcome.

T 4.3 Suitable architecture of the legislation on hydrogen

New markets and new value chains require new standards and new regulations. The existing legal literature concentrates on the identification and removal of entry barriers to establish markets for hydrogen (Banet, 2021b). In particular, to stimulate the deployment of fuel cells and hydrogen applications (HyLAW Online Database). However, a legislation for an integrated energy system that includes hydrogen and CO_2 has not been addressed. This will be the purpose of Task 4.3.

Facing a period of extensive legislative reforms for the implementation of the EU Green Deal and national policy objectives, this task will consider the best manner to structure the legislation sustaining an integrated energy system that includes hydrogen and CO_2. The research will start by recalling the objective and scope of application of the EU legislative acts that are relevant for a market for hydrogen. The next step is to discuss what should be the more appropriate architecture in the future. The deployment of hydrogen and regulation of related markets are covered by several directives, including REDII on the promotion of energy from renewable energy source, and the electricity and gas directives on market design rules. When revising REDII and the gas directive, the European legislator should pay attention to the whole architecture of the EU energy and climate legislation. This research will assess what should be the suitable architecture of the legislation for hydrogen at the EU level, i.e., a system of rules being consistent and coherent, designed to support general policy targets for hydrogen.

<u>A brief risk assessment</u>

- *Scientific staff*. If some of the researchers quit their jobs, they may still continue working on the project at the new work place. If some researchers leave the research industry, there are competent researchers available among the partners that can join the project team.
  Scientific challenges. If some the developed theory models become too comprehensive to be solved/tractable, one can either developed simpler model, typically to tailor-made each model to one narrow research question instead of having one comprehensive model to answer a set of research questions. Alternatively, the theory model is calibrated and simulated by computers. This strategy will provide answers to policy questions, but no general result can be derived. If, hypothetically, any of WPs 1, 2 or 3 are less successful than expected, the corresponding part in WP 4 will be simplified. Per construction, research is a risky business.

1.3 Novelty and ambition

The project is novel in several respects.

First, because there is no commercial market neither for stored CO_2 nor hydrogen, it is really hard to predict traded volumes. For example, DNV GL (2019) predicts that demand for hydrogen in Norway will increase by around one third over the next ten years, thereby being around 0.25 Mt in 2030. Equinor (2019) presents alternative scenarios for annual storage of CO_2 on the Norwegian continental shelf, ranging from 1.5 to 100 Mt of CO_2. The methodological basis for these predictions is not clear. In contrast, drawing on the industrial organization literature in economics and outputs from work packages 1-3, in work package 4 we will develop a model that integrates value chains for CO_2 and blue hydrogen as well as markets for fossil fuels and electricity. After calibrating the model, we can predict traded volumes of CO_2 and hydrogen. This exercise will be undertaken under alternative assumptions about the EU climate policy and also whether the EU sets strategic targets for hydrogen, confer the EU strategy to build up capacity for electrolysers, see European Commission (2020b).

Second, our discussion of the value chains for CO_2 and blue hydrogen will be complemented by an analysis of interlinkages between potential storage sites across Europe. Norway has, through the Northern Lights project, chosen to be a first-mover to offer CO_2 storage. We will explore whether the Northern Lights project is a game changer, that is, once this project materializes, will other similar projects follow without any, or much, government support? More generally, we will analyze whether there are any net economic benefits for Norway of being the first mover. To the best of our knowledge, our project is the first economic study to combine elements of imperfect competition, economies of scale, learning, and coordination problems in studying the possibilities for a future market for CO_2 transport and storage.

Third, the Norwegian government will fund around 75% of the costs of the Northern Lights project, see OED (2020). This division of funding and risks between the government and private firms will hardy continue. As part of the project, we will provide new knowledge of how alternative business models for the CO_2 value chain will work, and how the government can design instruments that incentives socially desirable investments in the CO_2 value chain.

Finally, new markets and new value chains require new standards and new regulations. The existing legal literature concentrates on the identification and removal of entry barriers to establish markets for hydrogen. However, a legislation for an integrated energy system that includes hydrogen and CO_2 has not been addressed, and will therefore be part of the project.

2. Impact

2.1 Potential for academic impact of the research project

First, the key challenge in developing value chains for CO_2 and hydrogen is to overcome the coordination problem, i.e., to ensure that a technology that is welfare improving is in fact installed and used. In Golombek et al. (2021), we have drawn on three strands of the economics literature—industrial organization, imperfect competition and economic geography—to develop a framework for examining the coordination problem of the CO_2 value chain, when also other characteristics of this chain, like economies of scale, are taken into account. We believe this is a significant contribution to the literature. In the planed project, we will expand the analysis in Golombek et al. study by considering coordination problems in *both* the hydrogen and the CO_2 value chain; these are interlinked as blue hydrogen producers need to store the removed CO_2.

Second, we will combine political science and economics to study the evolution of social acceptance for CCS and whether the government through incentives, regulations or informal signals can shift the outcome to one with substantial investment in CCS. To the best of our knowledge, this multidisciplinary approach to the dynamics of social acceptance will be new to the literature.

2.2 Potential for societal impact of the research project

This project analysis how development of a value chain for CO_2 and also a value chain for blue hydrogen will facilitate transition to a low-emissions society. This is in line with the EU goal to reach a climate neutral economy by 2050, which the European Parliament endorsed through its resolution on the European Green Deal, see European Parliament (2020). Carbon capture, which is part of the CO_2 value chain, might be of key importance in order to reduce CO_2 emissions from industrial activities that can hardly be electrified. Through increased supply of environmentally friendly hydrogen, total production of energy might increase, which should push down energy prices. Hence, development of value chains for blue hydrogen and CO_2 will contribute to two of the UN sustainable development goals, namely goal number 7, affordable and clean energy, and goal number 13, climate actions.

2.3 Measures for communication and exploration

The target audience cover private firms and public bodies, both domestically and in Europe, that are, or expect to be, involved in the value chains for hydrogen and CO_2 in Europe. For the domestic public sector, this includes the Ministry of Petroleum and Energy, The Ministry of Climate and Environment, as well as Gassnova. For domestic firms, this includes Norcem, which is now part of the Langskip project, Fortum Oslo Varme, which may become part of the Langskip project, and Equinor, which is part of the Langskip project as one of the owners of the Northern Lights facilities.

The results from this project will be communicated through publications in peer reviewed scientific journals. We will give high priority to research quality; hence our aim will be to publish our findings in prestigious journals, both field journals and general journals. We expect 7 publishable research papers in total. In addition, we expect to write four position papers, one for each WP. Finally, a policy paper summarizing the key findings from the project and providing policy advices will be the output from a policy forum organized by the project jointly with the reference group of the project. This group will follow the progress of the project, provide industry perspectives, and support with data and industry experience. The confirmed members of the group are (see attachment): Egil Meisingset (**Norwegian Ministry of Petroleum and Energy**), Jim Stian Olsen (**Aker Carbon Capture**), Johnny Stuen (**Fortum Oslo Varme**), Per Brevik (**Norcem**), Per Sandberg (**Equinor**), and Ståle Aakenes (**Gassnova**). We will seek to extend the group, for example, by including NGOs. Members of the reference group will be in a good position to communicate the main results from the project to their professional networks. The project leader of this proposal will organize the activities of the reference group.

Prior to final publication in journals, all results from this research project will be communicated through various working paper series and through presentations at workshops, seminars, and research conferences. All research outputs will also be communicated through a web-page.

In addition, we intend to reach out to politicians, policy makers working for government bodies, decision-makers in the industry, NGOs and a wider audience through newspaper articles, presentations and meetings, including organizing user-oriented seminars. In fact, some of the project participants are in contact with policy makers, actively participating in the media dialogue, including participation in government-appointed commissions.

3. Implementation

3.1 Project management and project group

We have assembled a multidisciplinary group of four economists (Dr. Knut Einar Rosendahl, Dr. Mads Greaker, Dr. Rolf Golombek and Dr. Snorre Kverndokk), two political scientists (Dr. Lars Gulbrandsen and Dr. Tor Håkon Jackson Inderberg), one lawyer (Dr. Cathrine Banet), two technology experts (M.Sc. Julien Meyer, M.Sc. Rolf Nyborg) and one scientist (M.Sc. in geophysics, executive master in technology management, Mari Lie Larsen) from research groups in the Oslo region—the Frisch Centre (host institution), the Fridtjof Nansen Institute, the Institute for Energy Technology, the Norwegian University of life sciences (School of economics and business) and the University of Oslo (Faculty of law). All participants have experience and academic records on CCS oriented research. In addition, the project will fund a PhD student at the Norwegian University of life sciences (School of economics and business), with four supervisors from the project team.

Most of the group was part of CREE – the Oslo Centre for Research on Environmentally friendly Energy, see https://www.cree.uio.no/, a research group for social science-related energy research (FME Samfunn) that was funded by the Research Council of Norway between 2011 and 2019. Golombek, who was the director of CREE, will be the project manager. He has been with the Frisch Centre since 1990, and has 30 years of experience as a project manager. Golombek has mainly worked within the fields of energy economics and environmental economics, both on applied economic theory and empirical studies.

3.2 Project organization and management

The project is organized through work packages, see the Gantt chart. There is no need for any specific infrastructure other than standard computers. In the budget, a specific amount of money is allocated to travels under the activity T1.1., outreach activities, organize the reference group, and to organize a Policy Forum. The Gantt chart shows participation in tasks by person. Note, however, that the PhD student has not been included in the teams shown in the Gantt chart; which tasks the PhD student will work on will be decided later, by taking into account the knowledge and preferences of the student.

Gantt chart: Tasks and teams (team leader in bold)	2021		2022				2023				2024				2025			
	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Project management	Project manager: <u>Golombek</u>																	
General management and organize reference group	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Hiring PhD student	■	■	■															
Organize Policy Forum														■	■	■		
WP 1 Social acceptance and demand for storage	Team: <u>Gulbrandsen</u>, Inderberg, Kverndokk																	
T1.1 Social acceptance and industry demand			■	■	■	■	■	■	■	■	■	■	■	■				
T1.2 Dynamics of industry demand							■	■	■	■	■	■	■	■	■	■	■	■
WP2 Competition and coordination of storage	Team: <u>Banet</u>, Kverndokk, Nyborg, Meyer, Rosendahl																	
T2.1 Competition for storage	■	■	■	■	■	■	■	■	■	■	■	■						
T2.2 Resource management and integrated planning			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
WP 3 Business models for developing value chains	Team: <u>Greaker</u>, Banet, Golombek																	
T3.1 Risk sharing schemes			■	■	■	■	■	■	■	■								
T3.2 *Assess business models from a legal perspective*			■	■	■	■	■	■	■	■								
WP 4 EU markets for hydrogen and captured CO_2	Team: <u>Golombek</u>, Banet, Greaker, Nyborg, Meyer																	

T4.1 EU support for developing value chains	■	■	■	■	■	■	■	■	■	■	■	■						
T4.2 Numerical model for hydrogen and captured CO_2					■	■	■	■	■	■	■	■	■	■	■	■	■	■
T4.3 Suitable architecture of the legislation on hydrogen											■	■	■	■	■	■	■	■

References

Banet, C. (2020). Havvind, hydrogen, CCS: Norge trenger en helhetlig energiplan for Nordsjøen. *Energi og Klima* nettmagasinet, 22.09.2020. https://energiogklima.no/kommentar/havvind-hydrogen-ccs-norge-trenger-en-helhetlig-energiplan-for-nordsjoen/

Banet C. (2021a). Regulering av karbonfangst, transport og lagring i norsk rett in H.-C. Bugge (ed.), *Klimarett.* Universitetsforlaget.

Banet C. (2021b). Hydrogen and CCUS compatible gas networks: identifying legal principles for gas market re-design. OGEL.

Chou C. and O. Shy (1990). Network effects without network externalities, *International J. of Industrial Organization* 8: 259-270.

Dermont, C., K. Ingold, L. Kammermann and I. Stadelmann-Steffen (2017). Bringing the Policy Making Perspective in: A Political Science Approach to Social Acceptance. *Energy Policy* 108: 359–368. doi:10.1016/j.enpol.2017.05.062.

DNB GL (2019). Produksjon og bruk av hydrogen i Norge. Rapport 2019-0039. DNV GL.

Equinor (2019). Northern Lights Contribution to Benefit Realisation. Retrieved 31 January from Socio-Economic Analysis - Fullskala (ccsnorway.com)

European Commission (2020a). Hydrogen generation in Europe: Overview of costs and key benefits. European Union. 2020.

European Commission (2020b). A hydrogen strategy for a climate-neutral Europe. COM(2020) 301 final. Brussels, 8.7.2020.

Farrell, J. and G. Saloner (1986). Installed base and compatibility: innovation, product preannouncements, and predation. *American Economic Review* 76, 940–955.

Gabriel, S.A., K.E. Rosendahl, R.G. Egging, H. Avetisyan and S. Siddiqui (2012). Cartelization in Gas Markets: Studying the Potential for a "Gas OPEC", *Energy Economics* 34, 137-152.

Golombek, R., E. Gjelsvik and K. E. Rosendahl (1998). Increased Competition on the Supply Side of the Western European Natural Gas Market, *The Energy Journal*, 19(3): 1-18.

Golombek R., M. Greaker, S. A. C. Kittelsen, O. Røgeberg and F. R. Aune (2011). Carbon capture and storage technologies in the European power market, *Energy Journal,* Vol. 32, 209-238.

Golombek, R., A. Lind, H-K Ringkjøb and P. Seljom (2020). The role of transmission and energy storage in Eurpean decarbonization towards 2050. Submitted to Energy.

Golombek, R. M. Greaker, S. Kverndokk and L. Ma (2021). Transition to carbon capture and storage technologies. Mimeo. Submitted to the 26th Annual Conference of the European Association of Environmental and Resource Economists.

Greaker, M. and K. Midttømme (2016). Network effects and environmental externalities: Do clean technologies suffer from excess inertia?, *Journal of Public Economics*, 143: 27-38.

IEA (2018): World Energy Outlook 2018, IEA/OECD. Paris, France.

Inderberg, T. H. J. and J. Wettestad (2015). Carbon Capture and Storage in the UK and Germany: Easier Task, Stronger Commitment? *Environmental Politics* 24 (6): 1014–1033. doi:10.1080/09644016.2015.1062592.

IRENA (2020). Green hydrogen. A guide to policy making. International Renewable Energy Agency.

Labriet, M., A. Kanudia and R. Loulou (2012). Climate mitigation under an uncertain technology future: A TIAM-World analysis. *Energy Economics*, Vol. 34, Supplement 3, S366-S377.

Massol, O. and A. Banal-Estañol (2018). Market power and spatial arbitrage between interconnected gas hubs. *The Energy Journal*, 39(Special Issue 2).

O'Brien, A. and C. Banet (2021). De-risking the H2-CCS value chain through law. *European Energy and Environmental Law Review*, 30(2).

OED (2020). Langskip – fangst og lagring av CO_2. Meld.St. 33 (2019-2020). The Norwegian Ministry of Petroleum and Energy.

OED and KMD (2020). Regjeringens hydrogenstrategi. På vei mot lavutslippssamfunnet. Retrieved 31 January from regjeringens-hydrogenstrategi.pdf

Oei, P.-Y. and R. Mendelevitch (2016). European Scenarios of CO_2 Infrastructure Investment until 2050. *The Energy Journal*, Vol. 37, special issue, 171-194.

Sandholm, W. H. (2020). Evolutionary Game Theory, in M. Sotomayor, D. Pérez-Castrillo and F. Castiglione: Complex Social and Behavioral Systems - Game Theory and Agent-Based Models, Springer.

Van Vuuren, D.P., M. Isaac, M.G.J.d. Elzen, E. Stehfest and J.v. Vliet (2010). Low stabilization Scenarios and Implications for Major World Regions from an Integrated Assessment Perspective. *The Energy Journal*, Vol. 31, Special Issue, 165-191.

Wolsink, M. (2020). Distributed Energy Systems as Common Goods: Socio-Political Acceptance of Renewables in Intelligent Microgrids. *Renewable and Sustainable Energy Reviews* 127 (March). Elsevier Ltd: 109841. doi:10.1016/j.rser.2020.109841.

Wüstenhagen, R., M. Wolsink and M. J. Bürer (2007). Social Acceptance of Renewable Energy Innovation: An Introduction to the Concept. *Energy Policy* 35 (5): 2683–2691. doi:10.1016/j.enpol.2006.12.001.