Network effects and excess inertia: Do Carbon Capture and Storage Technologies Suffer from Technology Lock-In?

Cassandra Velten

Working Paper 07/2017

The CREE Centre acknowledges financial support from The Research Council of Norway, University of Oslo and user partners.
ISBN: 978-82-7988-245-9
ISSN: 1892-9680
http://www.cree.uio.no

Abstract in Norwegian:

CREE - Working Paper 07/2017

Nettverkseffekter og "excess inertia"[1]:

Lider Karbon fangst- og lagrings teknologien (CCS) av teknologi Lock-in

Cassandra Velten, Masteroppgave

Utbredt bruk av CO_2-håndtering er mest sannsynlig nødvendig hvis verden skal nå 2-gradersmålet. Både IPCC (2014b) og IEA (2016) hevder at CCS er essensielt hvis klimamålene skal nås på en kostnadseffektiv måte. Det er i dag likevel få CCS-kraftverk under planlegging ettersom prisen på CO_2 ikke er høy nok slik at aktørene ikke betaler tilstrekkelig høy pris for sine utslipp til at de ikke har insentiver til å investere i CCS.

Denne oppgaven analyserer eksistensen av "lock-in" i CCS-markedet. Modellen er et en-periodespill mellom kraftverksprodusenter og produsenter av CO_2 transport- og lagringstjenester. Kraftverksprodusentene investerer enten i et CCS kraftverk, eller i et tradisjonelt kraftverk som slipper ut CO_2 i atmosfæren. Deretter simuleres modellen ved å bruke realistiske kostnadsestimater fra IEA (2015) og Rubin et al. (2015). Analysen viser at CCS-markedet genererer "excess inertia" i noen av de analyserte tilfellene. Dette innebærer at investeringer i CCS ikke blir gjennomført selv om de er lønnsomme. Aktørenes forventninger til karbonskatten og tilleggskostnaden ved CCS synes å være av særlig betydning for hvorvidt markedet genererer "excess inertia".

[1] «Excess inertia» betyr at teknologien som kom først, har en fordel slik at selv om det fins en potensielt velferdsfremmende annen teknologi, kommer denne ikke inn i markedet.

Network effects and excess inertia: Do Carbon Capture and Storage Technologies Suffer from Technology Lock-In?

Cassandra Velten

Master of Philosophy in Economics

Department of Economics

University of Oslo

May 2017

Network effects and excess inertia: Do Carbon Capture and Storage Technologies suffer from Technology Lock-In?

http://www.duo.uio.no

Publisher: *Reprosentralen,* University of Oslo

Network effects and excess inertia: Do Carbon Capture and Storage technologies suffer from Technology Lock-In?

Cassandra Velten

Preface

I would like to thank my inspiring supervisor Mads Greaker for excellent guidance. He has provided great feedback and constructive comments throughout the writing of this thesis. I am also grateful to the Oslo Centre for Research on Environmentally friendly Energy (CREE) for awarding me their master scholarship. I would also like to thank my friends for support, proofreading and fruitful discussions, you know who you are.

Any remaining errors in this thesis are my responsibility alone.

Abstract

CCS is cited as a critical technology for mitigating climate change. Deployment of CCS has, in contrast, been painfully slow. This thesis analyzes the existence of lock-in in the market for CCS. The model features a one stage game between power plant producers and producers of CO_2 transport and storage services. The power plant producers choose whether to invest in a power plant with carbon capture technology (CCS), or to invest in a power plant which emits CO_2 directly into the atmosphere. The model is then simulated using realistic estimates on the CCS supply chain. The analysis finds that the CCS market suffers from excess inertia in some of the analyzed scenarios. The carbon tax expectations of producers and the add-on costs of CCS seem to be of particular importance of whether the market generates excess inertia.

Contents

List of Tables

List of Figures

1 Introduction

Few now challenge the occurrence of climate change, or that it is driven by too high concentration of greenhouse-gases in the atmosphere. According to IPCC[1], climate change "will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems" (IPCC 2014a, p.8). In addition, time is of the essence: Analyses conducted by the IEA (2015) show that the difficulty and cost of climate change mitigation rise continuously. There is therefore an urgent need to reduce emissions, particularly of CO_2.

According to the IEA (2016), carbon capture and storage (henceforth CCS) is a critical technology for mitigating climate change. The agency forecasts that by 2050, in the 2DS scenario[2], 6 billion tons of CO_2 is captured using CCS. Similarly, a recent report from the IPCC found only four scenarios in which it was possible to reach the 2DS without CCS. The estimated costs in these scenarios were however 138 % higher than the most cost-effective scenario with extensive deployment of CCS (IPCC 2014b). Similar results are found by Krey et al. (2014) which assess the results of ten studies in which the pathway to the 2DS is analyzed. They find that without CCS, the costs of reaching the 2DS increases from 2 % of global GDP to more than 5 % of global GDP. The importance of CCS is also highlighted by the European Commission, which argues that CCS is the only cost-efficient technology which can successfully decarbonize Europe while securing the region's energy supply (Zep 2014).

Progress in deployment of CCS has, in contrast, been painfully slow. In spite of extensive government and private efforts, the technology has not had the anticipated kick-off. There are currently 17 CCS projects worldwide in development, which constitutes a significant reduction from 2014 when there was 24 projects in planning (IEA 2016). Two new CCS plants began operating in 2015, but no investment decisions were made. Meanwhile, international governmental financial support for CCS has declined. For instance, in November 2015, the British government cancelled a 1 billion £ CCS competition. In spite of some recent positive development, CCS is therefore far from being on track. As stated in a recent report by Oslo Economics (2016): "There is a need for urgency, but not a sense of urgency."

[1]Intergovernmental Panel on Climate Change

[2]2 Degree Scenario: Emissions trajectory consistent with at least a 50% change of limiting the average global temperature increase to 2° celsius, which is set out as the goal of the Paris Agreement. Source: IEA (2017)

In a newly published article, Midttømme and Greaker (2016) find that clean technologies may suffer from excess inertia due to network effects. As an example, they use carbon capture and storage technologies. They argue that, as a complementary pipeline transport service with economics of scale is required to deploy the technology, and as it is a complex service, it is likely that both quality and the cost of service will improve with the number of agents using the technology. A similar argument is posed by the Norwegian government. As part of the 360 MNOK grant for continued efforts on CCS in the Budget 2017[3], it awarded contracts to Klemetsrudanlegget, Norcem and Yara on April 19th. The aim is to complement CO_2 capture from these facilities by establishing a pipeline system with one on-shore terminal connected to an off-shore storage site to which the captured CO_2 will be transported.

In light of recent development on CCS, this thesis investigates how network effects can expand the understanding of market failures and commercial barriers related to the adoption and deployment of CCS. Specifically, if network effects indeed have important implications for the adoption of the technology, a more comprehensive understanding of these dynamics is crucial for the understanding of how carbon capture and storage technologies may be fully adopted. Otherwise, policy recommendations ignoring this aspect may have limited success in implementation. Using a theoretical framework based on the model by Greaker and Heggedal (2010) I address the following the research questions:

Will the presence of network effects of carbon capture and storage lead to a situation of technology lock-in?

In what ways do network effects affect market dynamics?

What are the implications of indirect network effects on public policy?

The thesis is divided into sections as follows. Section 2 describes the fundamentals of CCS technology, while section 3 discusses major barriers to commercial deployment of CCS. Section 4 provides a survey of the analytical framework of network effects applied in the thesis. The benchmark model is presented in section 5 and 6 while section 7 presents the numerical simulation using realistic estimates of the CCS chain. Sections 8-11 extends the model by providing simulations with altered cost estimates. Finally, section 12 discusses the results and concludes.

[3]Prop. 1S (2016-2017)

2 Carbon capture and storage technology

The process of carbon capture and storage prevents the release of large amounts of CO_2 into the atmosphere. The technology is essentially a three step process: CO_2 is first captured from industrial or fossil sources using an integrated or connected capture unit, before it is transported via pipelines or ships to a geological site where the CO_2 is stored in deep geological formations. See figure 1 for a visual representation of a CCS chain.

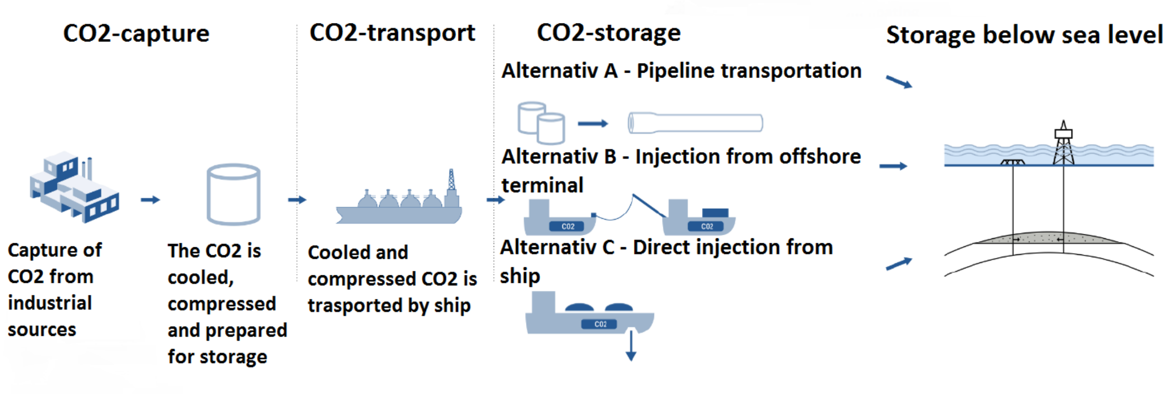

Figure 1: Presentation of a CCS chain Source: Oslo Economics (2016)

CCS is applicable for point sources that emits large amounts of CO_2 into the atmosphere, such as industrial sources or power plants. For industrial application, CCS is especially relevant for the production of cement, steel and aluminum, which all release large amounts of CO_2 into the atmosphere.

There are essentially three approaches to CO_2 capture for power plants. The carbon can either be removed from the fuel before the power generation process (pre-combustion). Alternatively, the carbon can be separated after the power generation process in an end-of-pipe solution (post-combustion). Finally, the fuel can be burned in oxygen instead of air (oxy-fuel combustion). At present, post-combustion is the most mature technology. Moreover, it is the only viable alternative for a retrofitted plant. However, the capture process is highly energy intensive, and reduces the power output of a new power plant by 15-25%. For an old power plant, the reduced power output may be substantially higher (Åkenes 2014).

The captured CO_2 can be transported to the storage site using pipelines or ships. Both technologies are mature and deployed commercially, for example for the transport of natural gas. However, especially transport by pipelines requires large upfront investments. The U.S. already have a quite extensive CO_2 pipeline system in place that has been developed for the purpose of EOR, as explained below, but the infrastructure would mostly need to be built from scratch in Europe (GCSSI 2017a).

Finally, CO_2 must be injected into the storage site. The CO_2 may be injected directly from a tank ship. Alternatively, it is possible to use a floating injection solution, where a tank ship is connected to a floating docking station. However, both technologies are not fully developed at present time, and thus imply substantial risk for an investor. A final alternative is to inject the CO_2 into the into the storage site using a pipeline. It is clear that especially the latter alternative would require substantial fixed entry costs for any commercial producer that would want to handle CO_2. However, if successful, a pipeline infrastructure could also give rise to "clusters" of CO_2 intensive industries.

At present, CO_2 for enhanced oil recovery (EOR) is the major use of CCS. It refers to a technique in which CO_2 is injected into an oil field in order to increase the amount of crude oil that can be extracted. Currently, 21 of the 32 CCS projects in advanced planning are intended for EOR (IEA 2016). Moreover, capture of CO_2 for the purpose of EOR is the only commercial use of CO2 at present time, and the only forseeable way that a market for CO_2 may be created. However, the climate benefit from EOR is minimal. As EOR is used for enhanced oil extraction, more oil is extracted. In addition, some of the CO_2 used for EOR is emitted back into the atmosphere with the extracted oil. This in turn reduces the total volume of stored CO_2. Thus, experts argue [4] that higher carbon prices is the only way to create a market for CCS.

[4] See e.g. EIA (2016), Zep (2014) and IPCC (2014a)

3 Barriers to commercialization of carbon capture and storage

The present section provides an introduction to challenges related to the development and adoption of the technology. The goal is to give an empirical backdrop and to motivate the analysis. The discussion does not aim to give a comprehensive explanation of *all* barriers and market failures related to CCS, but to identify and explain key barriers to adoption as identified in literature. The discussion follows the representation of Åkenes (2014) closely, but is also complemented with findings from two more recent articles published by GCCSI (2017a) and IEA (2016) .

In "From Moon-walking towards Moon-landing: How might CCS leave the Launch Pad?" (Åkenes 2014), Åkenes analyses key barriers to CCS adoption and deployment. In his analysis, he focuses on commercial barriers to implementation, which he defines as "barriers arising from market-driven factors" (p. 16). He motivates his focus by arguing that the impact of commercial barriers is underestimated in literature. By using Porter´s five forces framework, four key adoption barriers for CCS are identified: *the effect of high investment costs, the effect of changed cost structure, potential disadvantages from being a first mover on CCS and a new service provider.*

3.1 The energy sector and investments in CCS

The energy sector undergoes major changes. Electricity systems are transitioning from base load[5] operating conditions towards higher levels of intermittent energy sources, such as renewable energy. As the marginal cost of renewable energy is almost zero, it will have priority in the power grid once available. (Åkenes 2014). In contrast, flexible energy sources such as coal generated power will need to cut production when renewable power sources are available, and boost production when they are not. As renewable energy has attained a greater market share, profit margins in the coal energy sector has diminished. Åkenes argues that in a in a setting with smaller profit margins, a firm will strategically "divest (. . .) to reduce ownership in non-strategic assets and improve financial flexibility. (. . .) Any capital tied up in a CCS investment must therefore compete against other projects in a limited internal investment budget." (Åkenes, 2014,

[5] Power stations which can generate the energy needed to satisfy minimum level of demand on an electrical grid over 24 hours.

p. 34). Furthermore, renewable energy constitutes a diversified energy source compared to the traditional centralized base load power plant. In the current setting when the energy industry is moving towards greater use of distributed intermittent power, carbon capture and storage constitutes a traditional approach relying on centralized base load plants. Consequently, questions have been raised regarding whether "CCS plants will be able to sufficiently adjust its energy output in response to demand fluctuations throughout the day." (Brookings, 2015, p. 9)

In contrast to what is argued by Åkenes, we argue that the changing market conditions facing the energy industry constitute a force which discourages investments *both* in unabated power plants and in CCS power plants. Furthermore, we believe that base load power plants will continue to play an important role in European energy supply for the time period of analysis in this thesis (i.e. 2025-2030). For example, Germany has committed to phase out its nuclear fleet by 2022. At present, no renewable energy source is capable of ensuring a secure and reliable energy supply at sufficient scale for the country. As a result, the country has already announced the construction of several coal power plants which will contribute to fill the energy gap left by the phasing out of nuclear. Consequently, we have chosen to isolate our analysis to the comparison of investments in *base load* CCS power and *base load* unabated power.

In addition to the challenges posed by the changes in the energy sector, improved energy efficiency also constitutes a challenge for the profitability of a plant. In the "20-20-20" platform, the EU has targeted improved energy efficiency. The goal is to decouple economic growth from energy demand in order to improve sustainability. If successful, this poses a threat to fossil fuels as it reduces the potential for future market growth, which otherwise could justify investments and innovation at present. However, although this is cited as a barrier to investments in CCS, it is equally relevant for investments in fossil fuels in general.

3.2 The effect of high investment costs

In a setting with uncertain future market conditions and smaller profit margins, high investment costs compared to an unabated facility constitutes an important barrier to extensive investments in CCS. The additional capital costs required for CCS is often at the investment level of the power plant itself. Specifically, the capture process composes roughly 80 % of the add-on cost of CCS (Brookings, 2015).

Operating costs are also higher for a CCS facility than for an unabated facility. As capture of CO_2 is highly energy intensive, plant efficiency is reduced. This added energy penalty may range between 10-50 % of a facility´s net energy output (Brookings, 2015). These add-on costs will in turn directly influence the profitability of a plant, and may have large consequences for the attractiveness of CCS. Specifically, in the current setting where major trends transform the energy sector and future market conditions are uncertain, an investor will target particularly value-enhancing assets in order to ensure future competitiveness. By comparison, an investor risks being locked-in to a highly specialized asset with limited commercial value by investing in CCS. An owner of a coal power plant may be unwilling to make such a commitment to a technology with uncertain profitability. Furthermore, as argued by Blyth (2010), high uncertainty in the energy sector increases the option value of deferring an investment. As a result, a power plant owner may defer replacing old plants, or carry out other investments that could increase the lifetime of existing plants. For the specific case of CCS, this may imply that an investor might hold off investments in retrofitting carbon and capture or investments in newer plants with integrated carbon and capture technology until there is less uncertainty in the energy sector, or until the technology has clear commercial potential. In the present thesis, we include uncertainty by allowing the producers to have different expectations regarding carbon taxes. The carbon tax trajectory is up to 2020 is fairly certain. However, carbon taxes after this period is subject to a substantial degree of uncertainty amongst market agents.

The importance of high costs as an adoption barrier for CCS is also recognized by the IEA (2016). The agency cites too high costs of CCS relative to other power sources as the major challenge for extensive CCS implementation. They argue that in order for CCS to be employed at the scale required to reach the commitments defined by the Paris Agreement, it is imperative to reduce costs towards a level that ensures competitiveness with other low-carbon technologies.

3.3 The effect of changed cost structure

Another important barrier to deployment of CCS is the changed cost structure compared to in a traditional power plant. Changes in the cost structure will have a direct impact on the profitability of a power plant as the power market is highly price-driven. An investor must therefore carefully assess whether he will be able to recover the sunk investment costs of CCS. As CCS is not commercially competitive by itself, public regulation will have a decisive influence on the cost structure and the competitiveness of the technology.

To illustrate this point, Åkenes analyses the rate of CCS investments under a carbon tax and an emissions performance standard (EPS). A carbon tax increases the marginal cost for gas and coal power. However, the competitiveness of gas plants relative to coal plants will improve, as the CO_2 emissions per kWh produced for a coal plant is higher. He finds that under a carbon tax regime of $54 per ton, CCS coal is only the preferred technology if the plant operates at base load. For lower load factors, unabated coal could be more attractive than CCS coal even under strict environmental regulation. Under an EPS regime, the competitiveness of a gas plant relative to a coal plant improves even more compared to in the case with a carbon tax. Moreover, he finds that even under strict environmental regulations, unabated coal power could be more attractive relative to coal power of CCS. This is a result of CCS coal requiring a higher load factor to be an attractive alternative. However, Åkenes do not discuss the revenue side in his analysis. Therefore it is impossible to conclude based on Åkenes´ analysis whether power with CCS is indeed the profitable option.

Åkenes highlights that the competitiveness of coal power may be substantially challenged by alternative power sources such as hydropower, renewables and gas in the future. However, this argument is equally important for investments in traditional power plants as for investments in CCS and may not be considered an argument against CCS per se. In the present thesis, we assume that the unabated and a CCS power plant are operating under a given load factor so that the energy price is equal. In addition, we do not include gas power, and implicitly assume that it is more costly for the cases we are looking at.

3.4 First mover disadvantages

Another barrier to deployment is the risk entailed in operating a relatively new technology (Brookings, 2015). At present there is limited experience with the technology, and the CCS market is still in its infancy. Thus, there is uncertainty regarding how a full-chain CCS facility will operate. Specifically, an initial investor may face first mover disadvantages, such as technological and market uncertainty, incumbent inertia, technological discontinuities and free riding effects. According to Åkenes, such "first mover disadvantages would increase the expectations from the industry for public compensation beyond the actual costs" (Åkenes, 2014, p. 100). For example, due to the in-existence of a dominant design, a firm that is an early adopter of CCS risks being locked-in to an immature technology. Such technology lock-in could generate substantial cost and operational challenges for a firm. Moreover, due to the complexity of the technology, the size of these cost overruns could be substantial.

There may also be advantages of being a first mover on CCS. An early entrant has the potential to pioneer the market and thus earn substantial profits (Lieberman 1988). Specifically, an early entrant has more time to accumulate technological knowledge than rivals that come after him. A first mover may also get hold of important geographical locations or in other ways preempt scarce resources. In addition, early entry may give rise to a value net of transport and storage service providers or a customer base that finds it costly to switch to the offerings of later entrants. This would be valuable for a firm, especially if it has similar projects in planning. These potential first mover advantages may increase an investor´s willingness to pay for a new technology, and in turn limit the need for public co-funding. However, in the present context with high uncertainty related to the time-horizons of planned CCS projects combined with continued technological development, the learning from one project could be limited. Consequently, Åkenes argues that although there may be some first mover advantages, these are likely limited.

Also related to first mover disadvantages are spillover effects. Åkenes argues that a CCS project may give rise to consequential spillover effects to competitors, legislator, service providers etc. These spillover effect may be valuable for a firm as they contribute to market development. However, they will also be highly valuable to a firm's competitors. Hence, such spillover effects will most likely constitute a first mover disadvantage, and could also be an argument for public support.

Similarly, public perception may also constitute a first mover disadvantage for an entrant. Both Åkenes and the EIA (2016) cite public opposition as a major barrier to extensive adoption of CCS. The basis of the critique has been diverse, but is mostly related to the consequences of a CO_2 leakage. For instance, Greenpeace cites CCS as a "costly, risky distraction" and argues that the consequences for people and wildlife in case of leakage is too severe to justify investments in CCS (Greenpeace, 2017). Similarly, NOAH highlights the consequences for ground water contamination in case of leakage. As a result of public opposition, on-shore carbon storage is no longer considered a viable option in Europe (GCCSI 2017a). Public skepticism can therefore contribute to compound the risks of CCS projects.

First mover disadvantages is directly related to network effects, and is thus of specific interest to this thesis. As argued by Åkenes, a first-mover status by industry agents most likely confer disadvantages for the firm, which I will investigate in this thesis. Specifically, I will analyze whether the in-existence of a value net of service providers have an impact on the investment decisions of power plant owners.

3.5 The effect of a new service provider

The final barrier that Åkenes identifies is the effect of a new service provider. As argued by Moore (1991), a service may lose momentum when the service provider shifts from one customer group to another. As each customer group may have different attitudes towards risk or preferences, previous experience is not always transferable. Thus, for an investor, it is imperative to identify "the next costumer" when entering a new market segment. This may arguably imply extra risk and cost for the service provider, and may thus constitute a barrier towards technology investments.

Specifically, investments in CCS may introduce a new business model for the coal power industry. At present, the majority of current CCS facilities are used for the purpose of EOR by oil extractors. This is an entirely different business model than CCS utilized for climate change mitigation. Thus, Åkenes argues "moving the technology from one business to the other may introduce new challenges of implementation." (Åkenes, 2014, p. 101). There are at least two different forms of business models related to CCS. Either, one firm can be responsible for the entire CCS chain in an integrated business model. Alternatively, one firm can have ownership of the technology while a separate firm operates the technology. In these two business models, the allocation of risk between the participating agents is very different. For instance, under the EU directive, any CO_2 leakage is the economic responsibility of the owner of the storage facility. In a separated business model, this implies substantial risk for the owner of the storage site in case of leakage. "Any incidental leakage is to be compensated by purchase and surrendering of ETS allowances and that any damages on the environment is made up for" (Åkenes, 2014, p.102). In addition, the directive states that in case of storage closure, the storage provider is held responsible for all monitoring cost for a period of 30 years as well as the storage 20 years after closure. Thus, the magnitude of risk placed on a storage provider combined with low price incentives implies that the storage provider has little incentive to take on the risk. Furthermore, a separated business model generates a substantially more complex business model for a power plant choosing to adopt CCS. A separated business model adds a partner that controls close to 50 % of the total cost of the power plant, which constitutes a risk to the power plant.

In sum, out of the discussed market barriers, Åkenes argues that a general poor investment climate in the coal power industry due to high future uncertainty in combination with the added complexity in the business model constitutes the most important commercial barriers to CCS in the European coal industry. Comprehensive uncertainties regarding factor prices and future profitability amplify these challenges "beyond what could be found in most other industries"(p.110). Moreover, the amount of risk imposed on the storage provider by governmental regulations combined with a lack of a market for CO_2 storage obstructs investments in storage solutions.

3.6 The importance of infrastructure

A newly published report from GCCSI (2017a) cites two key barriers as potential "showstoppers" for commercial deployment of CCS. First, for CCS to be an efficient tool for climate mitigation, billions of metric tons of CO_2 must be captured yearly. This requires an extensive infrastructure for transport and storage which is currently not in place. Moreover, in order for CCS to be deployed at a scale aligned with the objectives in the Paris Agreement, development of such infrastructure will need to progress independently of individual capture projects. The report argues that "uncertainty over long term aspirations for CCS within the European portfolio of de-carbonization projects has created inertia to progressing CCS projects and to establishing a framework in which transport and storage infrastructure can be progressed ahead of market demand on the other." (GCCSIa, 2017, p. 16) In other words, the agency argues that the extent of risk concerning transport infrastructure and geological storage of CO_2 constitutes a major disincentive for commercial investments in CCS. Similar to the arguments presented by Åkenes, the agency highlights the lack of CCS projects combined with no clear potential of revenue for service providers as a major barrier to the adoption of the technology. The report argues that lack of commercial models and financing mechanisms have been the major showstoppers of European CCS success. Lack of necessary infrastructure for transport and storage as well as in-existence of a commodity CO_2 price has caused a climate of substantial skepticism towards the technical and commercial viability of the technology. Secondly, the agency cites the failure of coordination between potential providers of the service and emitters as equally important. This is the chicken and egg-problem; For a CCS facility to be built, an investor needs to be certain that there exist storage possibilities for the captured CO2, while a potential storage and infrastructure investor needs to know that there exists a demand for his service. Moreover, potential risk concerning future climate policy and the extent of government involvement and favorable regulations adds to the legal and technical risk of potential storage developers. In the report, they list three barriers that needs to be overcome for CCS to be commercially attractive (GCCSIa, 2017, p. 8):

- storage is not financeable/investible (capital market limitations)
- construction and performance risk (intra-chain risk)
- sovereign policy risk (change of law risk)

Thus, the report argues that in order to kick-start CCS investments, it is necessary to facilitate deployment of both part-chain and full-chain projects. Moreover, a policy framework is required that overcomes the disincentives of the private sector as well as ensuring that CCS technology is adopted at a sufficient scale.

3.7 The importance of CO_2 prices

As argued in section 2, climate policy will have a major influence on the future trajectory of CCS. CO_2 prices is essential in creating a market for CCS, and is the only incentive for the industry to invest in CCS. The cornerstone in EU´s policy to mitigate climate change is the EU emissions trading system (EU ETS). It is the world biggest carbon market, and covers around 45 % of the greenhouse gas emissions of the EU. The idea is that the higher level of carbon emission target is disaggregated into a stream of permits. In theory, the most efficient way to meet the overall objective is thus determined through supply and demand by the market. The EU ETS has however been criticized for not ensuring a sufficiently high carbon price as the level of permits is too high. At present, there is thus not a sufficiently high carbon price in place to incentivize investments in CCS.

4 Survey of existing literature on network effects

This sections provides a survey of the analytical framework of network effects. The purpose of this section is to give an analytical understanding of the definitions and concepts used in the thesis.

As cited by Farrell and Klemperer (2007, p 2007), “it can pay to coordinate and follow the crowd.” Network effects arise when the adoption of a good by one agent (a) benefits other adopters of the good; and (b) increases others‘ incentives to adopt it. (Farrell and Klemperer, 2007). Similarly, Leibowitz and Margolis (1995, p. 35) defined network effects as “ the circumstance in which the net value of an action is affected by the number of agents taking equivalent actions.”

Literature differentiates between direct and indirect network effects. Direct (or classic) network effects arise when the payoff of an agent is increasing in the number of agents that have already adopted the good, i.e. the good is complementary in adoption. For instance, Facebook becomes more valuable for a potential user if many of his friends already have user accounts; it is useful to speak Norwegian in Norway as many others do and a telephone is more valuable for an owner the more people he can call. The common denominator of these examples is that direct contact between the agents using the system increases the utility for all other consumers. The increased network size allows the agent to interact with a larger consumer base, which in turn increases his value of the service or good.

Indirect network effects features another important kind of network effects. Indirect network effects are related to the network size of a complementary network or product, which leads to a thicker market and increases the value of the original. As the number of agents consuming a good marginally increase, additional suppliers of a complementary good are incentivized to enter the market. Thus, the additional consumer attributes indirectly to the entry of additional suppliers.

Several authors in environmental economics analyze the implications of indirect network effects. Yu et al. (2016) analyze the network effects in the market for electrical vehicles (EVs). An agent chooses to either invest in a traditional gasoline car or an EV based on upfront costs, availability of charging stations and future operating costs, while an EV charging station maximizes profits by deciding whether to invest or defer investments to a later period. They find that, compared to the socially optimal allocation, the share of EVs relative to gasoline cars is too low. As a result of indirect network effects, the new technology does not diffuse sufficiently into the market. Moreover, the rate of diffusion is slower relative to what is socially optimal. Greaker and Heggedal (2010) analyze the transition to hydrogen cars by setting up a theoretical model where the existence of lock-in in the presence of network externalities is analyzed. In their model the presence of network effects is related to the number of hydrogen filling stations. They find that in the presence of network effects there may be multiple equilibria. Moreover, they find that when there are high costs in only one chain, the case of lock-in is less likely and the only equilibrium is with no hydrogen cars. Thus, in this case, the case for government intervention is less likely.

The importance of two-sided markets is also analyzed by Caillard & Jullien (2003) who claimed that one side of the market will always wait for the action of the other part of the market. Thus, the diffusion of a technology depends critically on agents making the "right" initial moves. Indirect network effects may also be important for carbon capture and storage. The more emitting firms that install carbon capture technology, the more attractive is it for investors of the technology.

Network effects most commonly refer to positive network effects, as in the examples listed above. However, network effects may also be negative, for instance in the case of congestion. This occurs when the value of a network decreases the more agents that use it. For instance, excessive traffic on a highway reduces the payoff for all users, due to increased traveling time, queue etc.

4.1 Excess inertia

From a cooperative game theory perspective, network effects are only economics of scale. However, issues related to coordination and contracting appear to be much more challenging. The adoption of a network encourages others to adopt the same network: By adopting network A, an adopter makes network A more attractive, meanwhile making the competing network B less attractive. As a result, network effects often create multiple equilibria and lead to problems of coordination.

Moreover, network effects may generate excess inertia. Inertia arises when "adopters remain compatible with the installed base even though an alternative would be better if network effects were neutralized" (Farrell and Klemperer 2007, p. 2029) Thus, a new and superior technology or industry can be "trapped" in spite of the switch being socially beneficial. Farrell and Saloner (1985) develop a simple model to investigate whether positive network externalities may inhibit innovation. They find that in a setting with ex ante identical firms with full information, the sequential timing of decisions will imply that the superior technology is fully adopted as long as all firms benefits from the shift to the new technology. Thus, excess inertia does not arise. However, incomplete information may generate excess inertia. All firms are "fence sitters": As no one has sufficiently high preferences for the technology switch, even if the total benefit from switching would exceed the transition costs, they all prefer to stick to the traditional technology. Thus, none of the firms have sufficiently high incentives to start the bandwagon by transitioning first. As a consequence, the economy never transition to the superior technology.

In a later article, Farrell and Saloner (1986) extend the model by allowing an already installed base of durables and private information among agents. In this setting, an industry with complete information may also suffer from excess inertia. As the new technology competes with an already installed base of a durable, it has an inherent disadvantage. Intuitively, those who adopt the new technology first, bear a disproportionate large fraction of the transition costs to the new technology. However, they also find that the industry can suffer from excess momentum, i.e. an over-adoption of the new technology. This is due to a first-mover advantage of those adopting the technology first, which makes the new technology more attractive to future adopters.

In a recent article by Midtømme and Greaker (2016), they analyze whether clean technologies may suffer from excess inertia. By developing a dynamic model with sequential timing they investigate the diffusion of a clean substitute to a dirty durable. A fraction of the durables wear out each period, and must be replaced either by a clean or dirty durable. This leads to changes in the market shares of the two durables over time. As a result of un-optimally set carbon taxes, excess inertia may arise in the adoption of the clean durable. Thus, the government must set the optimal carbon tax taking into account both the marginal damage of emissions and the network effect (plus the effect of monopolistic pricing in the presence of sponsors) Moreover, as the level of environmental damage affects the optimal provision of the two networks, small changes in the environmental damage from the dirty durable will lead to changes both in the Pigouvian tax and in the network effect. This is what they refer to as the "network interaction effect", which has important implications for the optimal tax rate.

4.2 The problem of lock-in

Various definitions of lock-in exist. Greaker and Heggedal (2010, p.14) define lock-in as a situation in which "two or more market equilibria exist, and in which the realized market equilibrium is welfare inferior to some unrealized equilibrium". Unruh (2000) argues that industrial economies suffer from carbon lock-in that arises due to increasing returns to scale. Systematic interactions between institutions and technologies create substantial barriers to alternative technologies. As a consequence, carbon lock-in impedes the diffusion of clean technologies even if they have clear economic and environmental advantages. Although carbon lock-in does not permanently preclude the shift to a cleaner technology, it can significantly delay this shift.

The definition of lock-in is closely related to the concept path dependence. Interpreted in the broadest sense, path dependence means that history matters. However, it implies that the initial starting point and "noise" will have significant consequences for the realized outcome. Margolis and Leibowitz (1995) present a taxonomy where they differ between three degrees of path dependence. First-degree path dependence refers to a situation in which an agent makes a choice that later turn out to be the best choice. The outcome is persistent, but there is no regret and hence no inefficiency. Second-degree path dependence is a situation in which the agents make an optimal choice of a durable, given their information at the time. Hence, even if later unanticipated event make the agents unsatisfied with their final choice, there is no lock-in or excess inertia, as the agents could not possibly have chosen any better. According to Leibowitz and Margolis, third-degree path dependence is the only inefficient outcome. It refers to a situation in which the agent makes a choice where another better feasible outcome was available at the time. That the outcome is feasible means that there was available information at the time about a superior alternative that the agent did not act on. Thus, the outcome is both inefficient ex ante and ex post. This is the only outcome that is policy relevant as the realized outcome could have been avoided, alternatively there could have been done something in order to minimize the loss. However, the authors argue that in these instances there is room for a private entrepreneur that internalizes the benefits of the transition and implement the optimal outcome. Moreover, market adaptions such as advertising, leasing, entrepreneurial actions etc. will alleviate lock-in. Therefore, third degree path dependence will be very rare: Lock-in will only occur in the instances where "an array of potentially profitable internalizing activities fail." (Margolis and Leibowitz, 1995, p. 12) Thus, in contrast to Unruh, they argue that the presence of increasing returns to scale and network effects is not sufficient to cause an inefficient outcome.

4.3 Technology sponsors

Is the adoption of a technology dependent on sponsorship? According to Katz and Shapiro, the answer is yes. Katz and Shapiro (1986) develop a theoretical model to analyze how the presence of network externalities affects the adoption of a technology. They find that the adoption of a technology is highly dependent on whether the technology is sponsored. The sponsor has property right of the technology, and is thus willing to forgo a loss today in order to increase the network size and increase his profits in the future. In absence of technology sponsors, the existing technology will in most cases dominate the market in the future. The reason being that the existing technology has a strategic first-mover advantage. As the consumer does not internalize the network effects when choosing which durable to consume, the equilibrium is distorted. Hence, sponsorship may internalize some of the externalities related to network effects.

However, Midttømme and Greaker (2016) find that excess inertia may occur even if the technology has a sponsor. Although the optimal tax is lower with a sponsor, the clean technology still not diffuses sufficiently into the market. Unlike Katz and Shapiro where the goods are perfect substitutes, the goods are horizontally differentiated in this model, which the authors claim may increase the probability of excess inertia. By harvesting the high-willingness-to-pay consumer, a low market share may be sufficient for the sponsor. However, excess inertia disappears once both technologies are sponsored. This is because it is easier to compete with a dirty sponsor that sets positive entry prices than a competitive durable sector.

4.4 Do network effects always imply network externalities?

The distinction between network effects and network externalities has not always been obvious. Early literature simply referred to network effects as network externalities. However, as Leibowitz & Margolis (1994) stressed, network effects do not automatically imply network externalities. Specifically, they argued that the majority of indirect network effects are pecuniary. Pecuniary effects refer to externalities that work through the price mechanism. For instance, if a firm marginally increases output that marginally lowers the price, this action hurt competing firms. However, the consumers benefit from the price reduction, which offsets the harm inflicted on the competing firms. Thus, this is simply a wealth transfer from firms to consumers and does not imply that the network effect is a network externality.

Farrell and Klemperer (2007) argue, in contrast, that economies of scale are often important in competitive industries. Therefore, there is an efficiency benefit of coordination, not just a pecuniary benefit. Moreover, they argue that network externalities only arise when pecuniary effects don‘t cancel out. For instance, the sponsor in the article by Farrell and Saloner internalized the potential benefit of adopting the technology and thus the shift to the superior technology. However, for this to be the realized outcome, a seller must accurately target adopters, which can be a challenge.

5 The stylized model

This thesis presents an augmented version of the model by Greaker and Heggedal (2010), which originally analyze network effects in the automobile market. The model features a one stage game between power plant producers and producers of CO_2 transport and storage services. The power plant producers choose whether to invest in a power plant with carbon capture technology (CCS), or to invest in a power plant which emits CO_2 directly into the atmosphere. The two types of power plants will be indexed $i \in \{A, U\}$ for "abated" and "unabated", respectively. If a producer chooses to invest in a facility without CCS, he must pay a carbon tax when emitting CO_2. In addition, whether a power plant producer chooses to invest in a facility with CCS is dependent on the density of on-shore terminals that is responsible for the transport and storage of CO_2. Meanwhile, the entry decision of CO_2 terminals is dependent on the number of power plants that have installed carbon capture technology. The size of the CO_2 transport network thus affects whether a power plant owner chooses to invest in CCS.

Following the original model of Greaker and Heggedal, we analyze a moderately sized country. That is, the marginal cost of carbon emissions is set equal to an international emission quota price or a carbon tax. Moreover, we impose the assumption that power plants and CO_2 transport and storage producers do not know the decisions of the other agents as they make their choice. Finally, we assume that power plant producers may only invest in *new* CCS power plants. That is, we abstract from investments in retrofit CCS power plants. This assumption is based on results from Greaker et. al. (2009), who simulate future demand for CCS power plants. They find that when using realistic values on carbon taxes, pre-combustion and oxy-fuel CCS become profitable. In contrast, extensive subsidies to technological development of retrofit CCS, in order to significantly reduce costs, are required before retrofitted CCS power plants become profitable.

5.1 Transport & Storage of CO_2

The CO_2 transport and storage producers are responsible for the pipeline transport system of CO_2, the storage site and the on-shore CO_2 terminals from which the captured CO_2 is transported to the storage site. Henceforth will refer to the CO_2 transport and storage producers as CO_2 terminals. Moreover, we abstract from any compatibility concerns in the pipeline system.

5.1.1 The Salop circle

Following the model of Greaker and Heggedal, supply of CO_2 transport and storage services is modeled after the Salop model (1979). In the Salop model, monopolistic market power is a result of spatial differentiation. Consumers live in city centre at the centre of a circle, and must adjust their driving pattern according to the distance to the nearest refueling station. The further the distance to a competing refueling station, the more expensive is it for a consumer to drive to a different station in terms of transport costs, and the higher markup may the refueling station charge.

In this thesis, the Salop circle will represent a pipeline transport system of CO_2, which is located at the central North Sea. Following Greaker and Heggedal's paper, the perimeter of the Salop circle is normalized to unity for simplicity.

The pipeline system consists of an off-shore storage site, located at the centre of the surrounding pipeline system. The off-shore storage site can for instance be interpreted as Sleipner, which is located at the centre of the North Sea. As the first operational CCS sequestration plant, it has stored more than 16 million tonnes of CO_2 in the Utsira formation since it began operating in 1996. Moreover, the Utsira formation is cited as one of the most promising storage formations on the European continental shelf. Estimates indicate that it is capable of storing 847 Mt[6] of CO_2 (GCCSI, 2017b). Furthermore, estimates indicate that it could store emissions from all industrial sources and power plants located in Northern Europe for several hundred years (Torp & Christiansen, 1998) Thus, Sleipner has the potential to constitute a storage cite for a surrounding network of CO_2 transportation in the future (See e.g. Statoil (2017), MIT (2016) & GCSSI (2017b)). Figure 2 illustrates the pipeline system in the North Sea, where for simplicity Sleipner is assumed to be located at the centre of the circle.

[6]mega tons

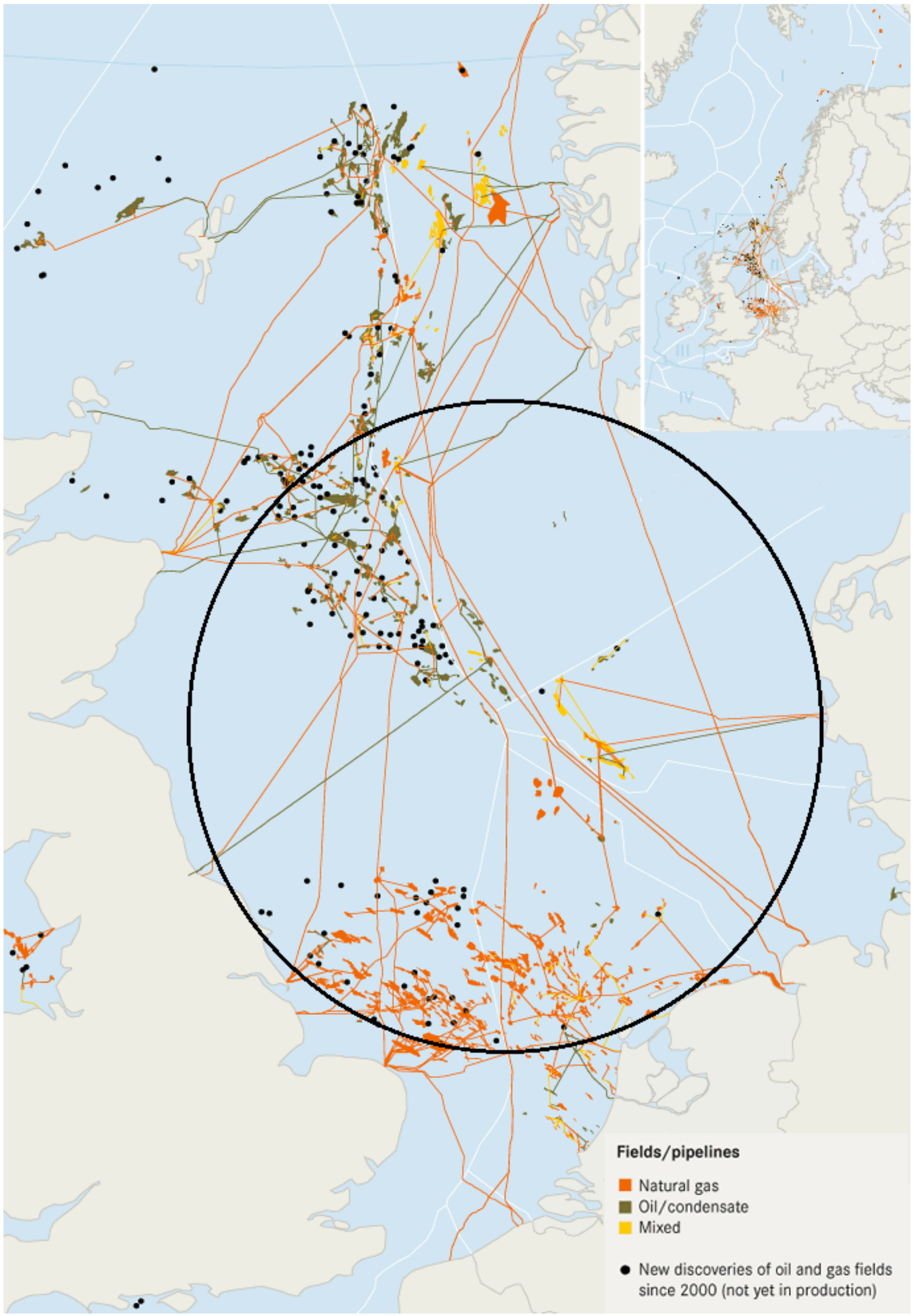

Figure 2: Map representing the Salop circle in the North Sea

The pipeline system also consists of on-shore terminals from which to transport CO_2 to the storage site, which are denoted by n^A. The terminals are connected directly to the CO_2 storage site, and are assumed to be uniformly distributed along the Salop circle. The distance between each terminal is therefore equal to $\frac{1}{n^A}$. Each on-shore terminal chooses its price of CO_2 storage. Hence, the price of CO_2 transport for on-shore terminal α is equal to p^A_α.

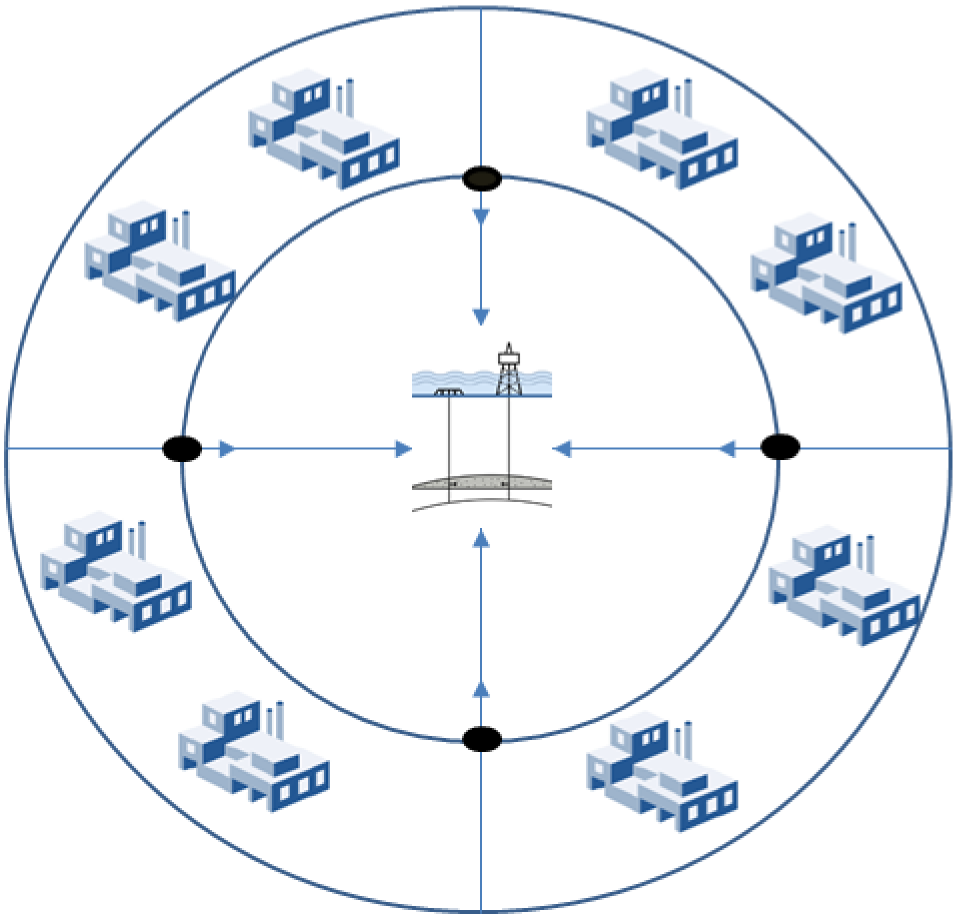

Figure 3: Illustration of the Salop circle, terminals and power plants

Figure 3 gives an illustration of the Salop circle when there are four terminals and eight power plants. As illustrated in the figure, power plants are located in the outer circle. The black nodes in the figure illustrates the CO_2 terminals. A power plant located between two terminals will choose to transport the captured CO_2 to the nearest terminal. The terminal will then transport the CO_2 via pipeline to the storage cite at the centre of the circle.

To simplify, we assume that power plant producers are located along the Salop circle, and must adjust the CO_2 transport route according to the distance to the nearest on-shore CO_2 terminal. The power plants care about their total cost of transport and storage. This consists of the price of CO_2 storage p^A, plus the traveling cost to the nearest on-shore terminal, t^A.

An abated power plant located at distance $x \in [0, \frac{1}{n^{\text{A}}}]$ from on-shore terminal α will have a total cost of CO_2 transport and storage equal to $p_\alpha^A + t^A x$. Therefore, a power plant located at distance x will be indifferent between purchasing CO_2 transport and storage from terminal α and its closest neighbor, terminal β, if:

$$p_\alpha^A + t^A x = p_\beta^A + t^A \Big(\frac{1}{n^A} - x\Big) \tag{1}$$

That is, if the the cost of purchasing CO_2 transport and storage from terminal α and β is equal. This cost consists both of the price of CO_2 transport and storage ${p_i}^A$, plus the traveling cost t^A in terms of time and transport costs, $i \in [\alpha, \beta]$.

In order to find the demand of each terminal, we solve equation (1) for distance x. As each terminal gets consumers from both sides, the distance is multiplied by 2:

$$2x = \frac{-p_\alpha^A + p_\beta^A + \frac{t^A}{n^A}}{t^A}$$

This denotes the share of power plants purchasing CO_2 transport and storage from terminal α as a function of the price of purchasing storage from terminal α, the price of purchasing CO_2 storage from β and the mark-up of each terminal $\frac{t^{\text{A}}}{n^{\text{A}}}$. The demand for CO_2 services from terminal α is then:

$$D_\alpha(p_\alpha^A, p_\beta^A) = 2xq^A = \frac{-p_\alpha^A + p_\beta^A + \frac{t^A}{n^A}}{t^A} q^A$$

where q^A is defined as $q^A = 1 - q^U$ and constitutes the market share of power plants with CCS. This specification defines demand as equal to the share of power plants that purchase CO_2 transport and storage services from terminal α times the total market share of power plants with CCS.

5.1.2 Pricing

Terminal α maximizes profits by maximizing price:

$$\max_{p_\alpha^A} \Big[(p_\alpha^A - c^A)\Big(\frac{-p_\alpha^A + p_\beta^A + \frac{t^A}{n^A}}{t^A} q^A\Big) - f^A\Big]$$

where f^A constitutes the fixed entry cost of building the pipeline system for each terminal.

Taking the first order condition yields:

$$\Big(\frac{-p_\alpha^A + p_\beta^A + \frac{t^A}{n^A}}{t^A}\Big) q^A + (p_\alpha^A - c^A)\Big(-\frac{1}{t^A}\Big) q^A = 0$$

In the following we impose the assumption that the solution is a symmetric Nash price-equilibrium. This implies that all terminals use the same price strategy in equilibrium, such that $p^A = p_\alpha^A = p_\beta^A$. The price of CO_2 transport and storage can then be written:

$$p^A = c^A + \frac{t^A}{n^A} \tag{2}$$

Equation (2) states that the price of CO_2 transport and storage is equal to the variable cost c^A plus the markup $\frac{t^A}{n^A}$. The variable cost equals the cost of CO_2 storage for each terminal. The markup is higher, the less terminals there are. This is a reflection of the monopolistic competition in the model: Each CO_2 terminal has monopolistic power over the power plants that is located close to it. The further the distance to the nearest terminal, the more costly it is for a power plant to transport the captured CO_2 to a competing terminal, and the higher markup can each terminal charge without losing market power. Likewise, if the distance between each CO_2 terminal is short, the cost of transporting the captured CO_2 to a competing terminal is low. Thus, each terminal has weaker monopolistic power, and must settle with a lower markup. For a given t^A, the number of CO_2 terminals therefore also determines the CO_2 transport and storage cost of a power plant.

As a result of free entry, CO_2 terminals will enter the market until their income barely covers the fixed cost of entry. That is, CO_2 terminals will enter until profits are equal to zero:

$$\frac{q^A t^A}{(n^A)^2} - f^A = 0 \tag{3}$$

Equation (3) defines the number of CO_2 terminals as a function of the market share of CCS. The first term is the income of each CO_2 terminal, which is defined as supply $\frac{q^A}{n^A}$ times the mark-up $\frac{t^A}{n^A}$. The second term is the fixed cost of building the CO_2 transport-network (i.e. the pipelines) f^A. By solving for n^A, we find the number of CO_2 terminals as a function of the market share of CCS power plants:

$$n^A = \sqrt{\frac{t^A q^A}{f^A}} \tag{4}$$

Equation (4) may also be interpreted as the best response function of each CO_2 terminal. That is, the strategy that generates the most favorable outcome for a CO_2 terminal when he takes the strategy of the other players as given. (Tirole and Fudenberg (1991).From the equation we see that the the number of terminals is increasing in the market share of CCS. The reason is that a higher CCS market share increases demand for CO_2 services, which in turn induce entry of CO_2 terminals. In addition, the best response curve of CO_2 terminals is decreasing in the fixed cost f^A. The intuition is that a higher cost of building the pipeline system and storage cite increases the cost of each terminal, and fewer are willing to enter. Thus, the terminal coverage for a given market share of CCS is lower. In the extreme case, pipeline costs are so high that no terminal is willing to enter. In that case, there is no realized equilibrium with a positive market share of CCS power plants. Finally, the number of terminals is increasing in the mark-up, t^A. For a given level of CCS power plants, the profit margin of each terminal increases. This in turn induces further entry of terminals, which will continue to enter until the profit margin is exhausted and the zero-profit condition is again satisfied.

5.2 The power plant producers

The power plant producers have inelastic demand for one type of power plant, and will either invest in an abated power plant with integrated carbon capture, or an unabated power plant. That is, we assume that the market is covered. The power plant producers are denoted by $i \in \{A, U\}$, for abated and unabated respectively. Throughout the thesis we will interchangeably refer to abated and CCS power plants and facilities. They have the same interpretation.

In Greaker and Heggedal's paper, demand for hydrogen cars is modeled along the model of vertical differentiation by Shaked and Sutton (1982). In the Shaked and Sutton model, products are differentiated with respect to quality. Consumers perceive the products as different, which is reflected in a taste parameter. This will have a decisive role in the purchasing decision of the consumer. As a result of the perceived differences in quality, price competition is dampened. Thus, heterogeneous tastes creates a setting in which competing firms may charge different prices.

This thesis, in contrast, presents a model in which each producer perceives an abated power plant with integrated CCS as equal in quality to a traditional, unabated power plant. That is they both produce a given amount of energy which can be sold for the same price. However, power plant producers are heterogeneous with respect to their expectations of a carbon tax. Specifically, each producer have certain beliefs regarding the level of the carbon tax, which in turn will have a decisive influence on whether he finds it optimal to invest in a power plant with CCS. Thus, our model differs from a model with homogeneous and rational expectations. With homogeneous expectations, all agents share the same beliefs, and will therefore make the same decision when facing the same economic problem. Hence, there is only one realized outcome. In contrast, determinacy properties may be significantly altered with heterogeneous expectations. Each agent makes the optimal decision given his beliefs, which need not coincide with the beliefs of another agent.

Each power plant maximizes expected profits. The profits of an abated power plant with CCS is given by:

$$\Pi_x^A = \Gamma^A - \frac{t^A}{4n^A} - \omega^A - p^A \tag{5}$$

Equation (5) states that the expected profits of an abated power plant with CCS is equal to gross revenue Γ^A, less costs, which consists of expected transport costs, power plant costs and the cost of storage which is paid to terminal owners. Gross revenue is assumed to be constant, which follows from the assumption that the market for power plants is fully covered. Costs ω^A of a power plant are assumed to equal the marginal cost of fuel and investments for an abated facility. Thus, we abstract away from monopolistic competition in the supply chain of CCS power plants. The expected traveling cost of CO_2 transport to the nearest CO_2 terminal is $\frac{t^A}{4n^A}$, which constitutes the average transport cost of each power plant. Finally, p^A is the cost of CO_2 storage.

By inserting for the price of carbon storage from the optimization problem of the CO_2

terminals, from equation (2), the profits of a CCS power plant can be written as:

$$\Pi_x^A = \Gamma^A - \frac{5t^A}{4n^A} - \omega^A - c^A$$

Similarly, the profits of an unabated power plant is given by:

$$\Pi_x^U = \Gamma^U - \omega^U - \lambda_x \tau \tag{6}$$

Equation (6) states that profits of a power plant without CCS equals gross revenue Γ^U, less power plant costs, ω^U and the carbon tax. Again, we abstract from monopolistic competition in the power plant supply chain by assuming that power plant costs are equal to the marginal cost of investment and fuels. Finally, as the power plant has not installed CCS, it will emit CO_2 directly into the atmosphere. Doing so, it must pay a carbon tax. Heterogeneous expectations regarding the carbon tax is reflected in a belief parameter λ_x, where $\lambda_x \in [0, 1]$. The belief parameter is multiplied with τ, which defines the maximum carbon tax per power plant. Specifically, we assume that $\tau = \theta \cdot 2DS$, where $1 \leq \theta \leq 2$ and 2DS equals the tax that yields the 2DS measure as total tax payment per year.

Thus, incorporated into the analysis is that carbon taxes need not be equalized across all sectors. Some sectors may face a different tax, or even be exempt from carbon taxes due to, for instance, lobbying. For example, in Norway, the agricultural sector will (most likely) be exempt from carbon taxes. If this is so, lower carbon taxes in some sectors must be corrected by setting higher carbon taxes for other sectors, such as the energy sector. Furthermore, we assume that the realized tax necessary to reach the 2DS is the average of the highest and lowest expected carbon tax, i.e. $\lambda_x^* = \frac{1}{2}$. Thus, if $\theta = 2$, then $Exp(\lambda_x \tau) = 2DS$ tax, and the agents have correct expectations on average. In contrast, if $\theta = 1$,agents have systematically too low expectations. If this is so, this might amplify any network effects. However, as a benchmark case we assume that the agents´expectations (on average) are correct, such that $Exp(\lambda_x \tau) = 2DS$. Finally, we assume that $\Gamma^A = \Gamma^U$.[7] That is, the gross revenue from an unabated power plant equals gross revenue from a power plant with CCS

[7]One may argue that it is likely that a carbon tax will influence the revenue of a power plant. Specifically, a high carbon tax will increase the price of electricity, which in turn will increase the revenue of an abated and unabated facility, all else equal. This could be reflected in a price effect, $\rho(\lambda_x)$, where $\rho´>0$, such that gross revenue of both an unabated and an abated power plant could be written as $\Gamma^i + \lambda_x \rho$, $i \epsilon \{A, U\}$. However, as these would cancel out, we leave it out of the analysis.

In order to solve the model, we need to find the marginal power plant producer which is indifferent between investing in an abated power plant and an unabated power plant for a given market share of CCS. This is found by setting the profits of an abated power plant producer equal to the profits of an unabated power plant producer:

$$\Pi_x^A = \Pi_x^U$$

This yields:

$$\Gamma^A - \frac{5t^A}{4n^A} - \omega^A - c^A - \left(\Gamma^U - \omega^U, -\lambda_x \tau\right) = 0$$

Using $\Gamma^A = \Gamma^U$, and solving for λ_x^* yields:

$$\lambda_x^* = \frac{\frac{5t^A}{4n^A} + (\omega^A - \omega^U) + c^A}{\tau}$$

The next step is to find the market share of CCS power plants and market share of unabated power plants. Using that $\lambda_x \in [0, 1]$, demand for unabated and abated power plants respectively is given by:

$$q^i = \begin{cases} \lambda_x^* = \frac{\frac{5t^A}{4n^A} + (\omega^A - \omega^U) + c^A}{\tau} \\ 1 \text{ - } \lambda_x^* = 1 - \frac{\frac{5t^A}{4n^A} + (\omega^A - \omega^U) + c^A}{\tau} \end{cases} \quad (7)$$

where $i \in [U, A]$. The market share of CCS power plants is thus:

$$q^A = \frac{\tau - \frac{5t^A}{4n^A} - \triangle\omega - c^A}{\tau} \quad (8)$$

where $\triangle\omega = \omega^A - \omega^U$. Equation (7) may be interpreted as the best response function of each CCS producer. That is, the strategy that generates the most favorable outcome for a producer when he takes the strategy of the other players as given. (Tirole and Fudenberg (1991) From equation (8), we see that the market share of CCS power plants is increasing in the carbon tax. The reasoning is intuitive: A higher carbon tax will increase the cost of an unabated power plant, and will make it more profitable to invest in a CCS power plant, all else equal. The term τ constitutes the highest belief of carbon tax payments of an unabated plant. As mentioned, the carbon tax is exogenous and constitutes the common factor between the beliefs of the agents. Consequently, it can shift in response to changes in outside conditions. For instance, the Paris agreement probably increased the expectations of the effectiveness of future international collaboration on climate change, and probably made the expected carbon tax a bit higher. In contrast, the market share of CCS power plants is decreasing in the mark-up, the add-on cost of a CCS power plant, and the storage cost of CO_2 for the terminals, respectively. As mentioned, the fewer onshore terminals there are, the weaker is monopolistic competition and the higher is the markup $\frac{5t^A}{4n^A}$, increasing the cost of a CCS power plant. Similarly, when the additional cost associated with investing in a CCS power plant $\triangle\omega$ is high, the smaller will the market share of CCS power plants be, for a given carbon tax. Finally, when the cost of storage for each terminal c^A is high, the realized market share will be lower as well as this will transfer into a higher price of CO_2 transport and storage for the power plant. Consequently, for a given carbon tax, fewer producers will invest in a power plant with CCS.

It is possible to solve directly for the market share of CCS power plants, as q^A is the only unknown variable. By inserting for n^A from equation (4), and defining $z = \sqrt{q^A}$, the equation can be written as:

$$z^3 - \frac{\tau - \triangle\omega - c^A}{\tau} z + \frac{5\sqrt{t^A f^A}}{4\tau} = 0 \tag{9}$$

This cubic equation is very similar to the one featured in the model of Greaker and Heggedal. Depending on the parameter values, the equation may have three real roots, where one is negative and two are positive roots. The potential market equilibria are represented by the two positive roots.

6 Equilibrium

The model can be solved analytically or graphically, where we have chosen the latter. In order to find the solution to this game, we need to find the level of CO_2 terminal coverage and the market share of CCS power plants such that no agent wishes to deviate from his chosen strategy. The game can be solved by drawing equation (4) and (8) in a (q^A, n^A)-diagram. As mentioned, equation (4) defines the best response function of each terminal for a given market share of CCS power plants. Similarly, equation (8) defines the best response of CCS power plant producers for a given level of CO_2 terminal coverage. In order to draw the equations in the same diagram, it is necessary to solve equation (8) for n^A. This yields:

$$n^A = \frac{5t^A}{4\left[\tau - \triangle\omega - c^A - \tau q^A\right]} \tag{10}$$

In figure 2, equations (4) and (10) are drawn in a (q^A, n^A)-diagram, for a given set of parameters. The market share of CCS power plants is depicted along the horizontal axis, and the CO_2 terminal coverage is depicted along the vertical axis. Supply of CO_2 terminals is depicted by the concave function, while the convex function depicts the best response function of CCS power plant producers. Further, the best response of CCS power plant producers intersects with the vertical axis at $\frac{5t^A}{4(h\tau - \triangle\omega - c^A)}$. This defines the lowest required value of n^A for investments in carbon capture. Note that there is an asymptote at $q^A = \frac{\tau - \triangle\omega - c^A}{\tau}$. However, we do not show this in the figure.

In figure 4, the Nash equilibria are where the best response function of CCS power plants intersects with the best response function of CO_2 terminals. At these intersection points, neither of the players wishes to alter their strategy, given the strategy of the other players.

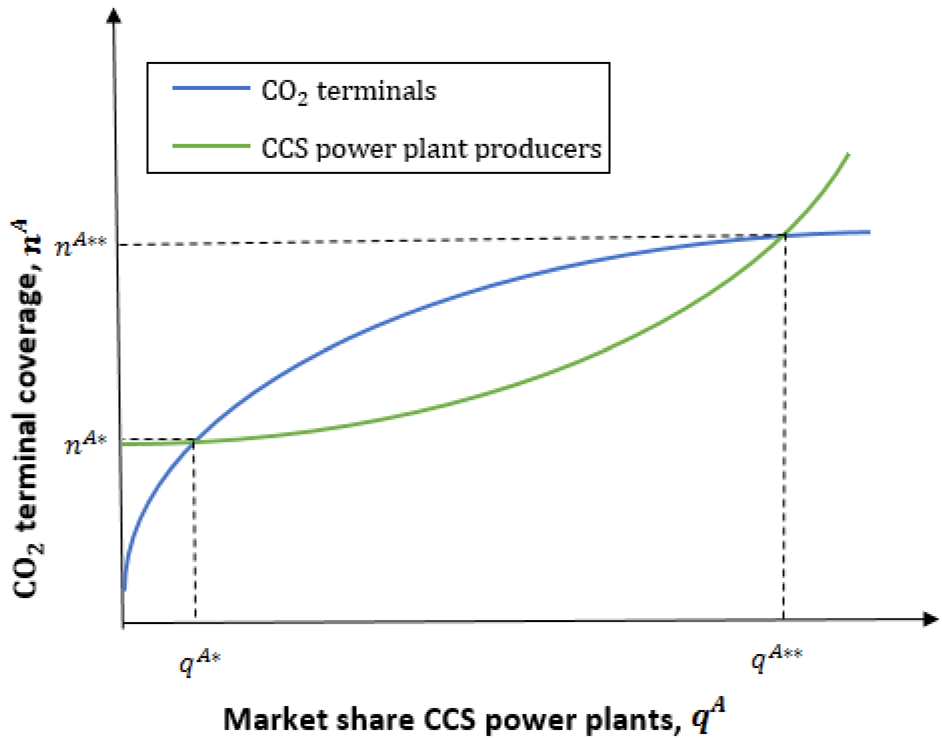

Figure 4: Equilibrium

As illustrated in figure 4, the equilibria either yield a high market share of CCS power plants, or an equilibrium with a low market share of CCS power plant. In addition, a zero market share of CCS power plants is also a Nash equilibrium as neither CO_2 terminals nor CCS power plant producers regret their choice in that case. As in the model of Greaker and Heggedal (2010), there may therefore be three analytical solutions. The graphical solution illustrates the two real roots of the game.

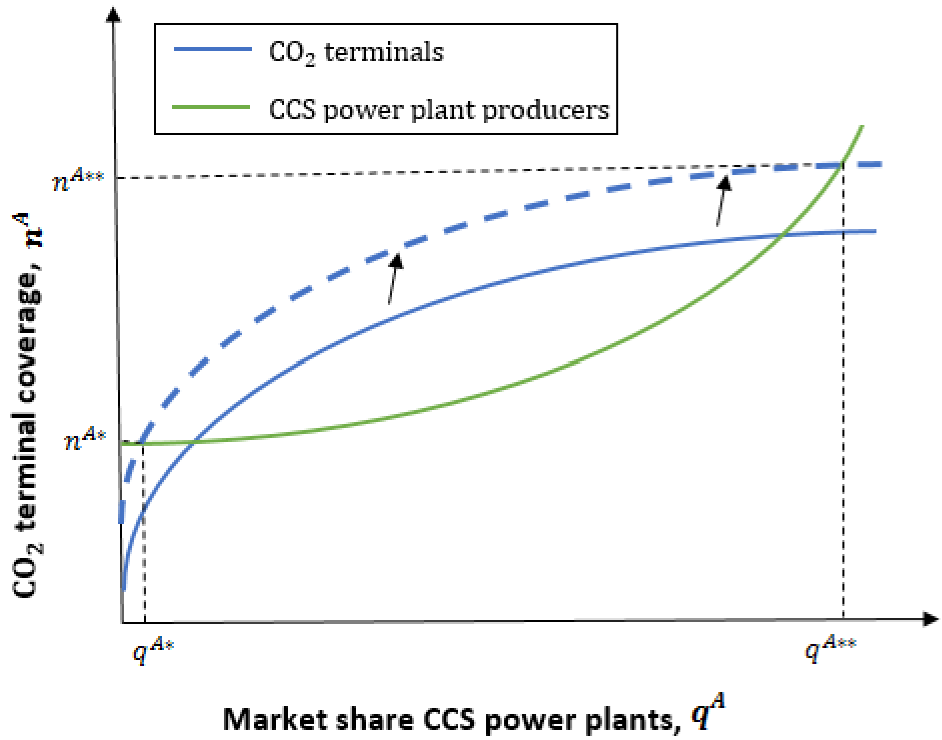

Figure 5: Equilibrium in which the fixed cost of CO_2 terminals is lower

Figure 5 illustrates the effect of reduced fixed costs. If the fixed cost of CO_2 terminals decreases (i.e. a lower f^A), the best response curve of CO_2 terminals shifts up in the diagram. This is because reducing the cost of building the pipeline system & storage site decreases the cost of each terminal. As a result, for a given level of CCS power plants, the profit margin of each terminal increases. This in turn induces further entry of terminals, which will continue to enter until the profit margin is exhausted and the zero-profit condition is again satisfied. As a result, the CO_2 terminal coverage is higher for a given market share of CCS power plants.

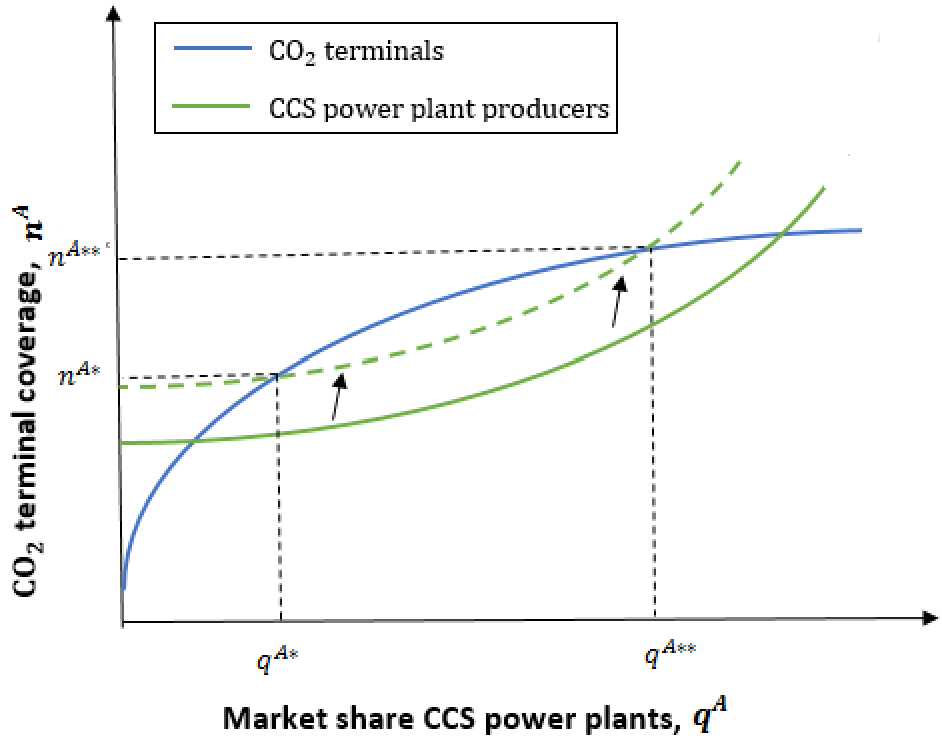

Figure 6: Equilibria in which the cost of CCS is higher

Similarly, increased costs for the power plant producers in terms of a higher $\Delta\omega$ or c^A shifts the best response curve of the power plant producers upwards in the diagram. This is illustrated in Figure 6. For a given coverage of CO_2 terminals, the add-on cost of CCS relative to unabated power is then higher. Thus, fewer power plant producers will invest in a power plant with carbon capture and storage. In contrast, a higher expected carbon tax (i.e. high τ) increases the attractiveness of CCS relative to a traditional fossil fuel plant as the producers believe that unabated fossil power will be more costly. As a result, the best response curve of the power plant producers shifts downwards in the diagram.

Note that the level of on-shore CO_2 terminals in the low equilibrium defines the critical mass of CO_2 terminals needed to keep the market self-sustaining. Any entry below n^A will reduce demand so that less and less terminals enter, leading to a collapse in the market. In contrast, any entry beyond this point will tip the market in favor of CCS power plants. Past the low equilibrium, the power plant producers who invest in traditional power plants will regret their choice, and will rather invest in CCS power plants as they otherwise will regret their choice. In response to increased investment in CCS power plants, more CO_2 terminals will enter the market. This process will continue until the high equilibrium is reached. Due to the concavity of the CO_2 terminal supply function, this equilibrium is stable: Entry of on-shore terminal beyond this point would lead to a diminishing increase in demand after CCS power plants. This process, in combination with a curbing profit margin for the CO_2 terminals, imply that terminals that enter beyond this point will regret entry. Figure 7 illustrate the dynamics towards the high equilibrium when n^A is slightly higher than the critical mass.

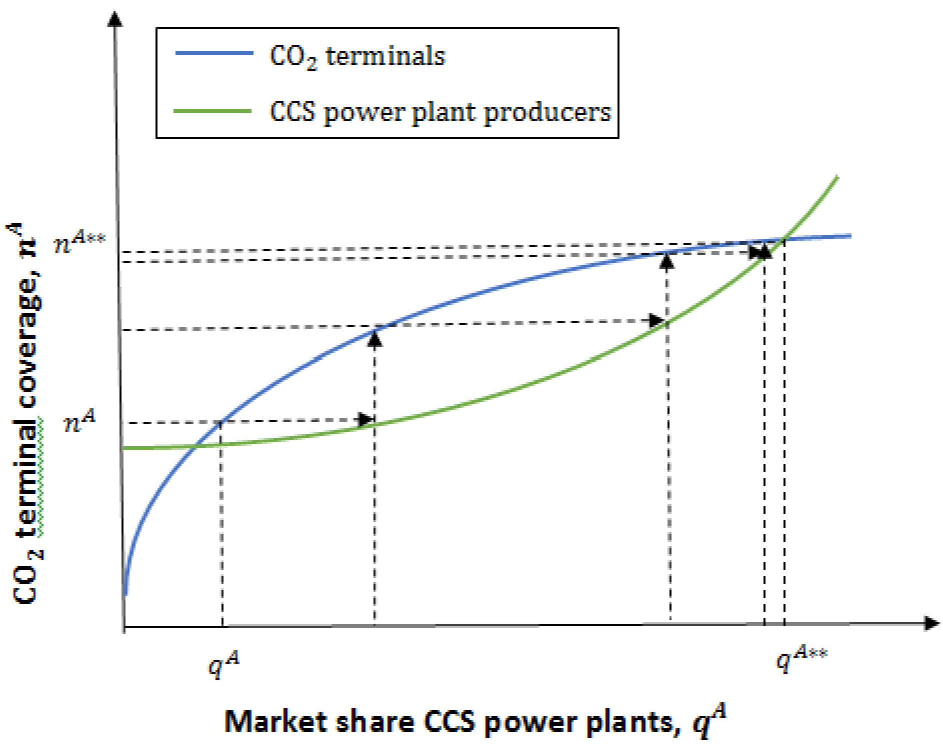

Figure 7: Equilibrium dynamics to the equilibrium in which CCS captures a high market share

7 Numerical simulation

The previous section gave an analytical presentation of the model. In the following, the model is simulated using realistic estimates on the CCS supply chain. The analyzed time period is 2025-2030. As the average lifetime of a power plant is 30 years, we analyze five years of a power plant´s lifecycle. We begin by identifying all cost components in the CCS chain and assess the cost drivers for each component, starting from the capture plant to the storage site. Then we present the results of the simulation and discuss the results.

The analysis includes transport of CO_2 by pipeline or by ship. Results from Gassnova (2016) and Oslo Economics (2016), which assess methods for CO_2 transport in the North Sea, find that transportation by ships is a viable option for transport of smaller volumes of CO_2. For transport over longer distances and for larger volumes, pipelines is less costly. Figure 8 illustrates the break-even point for pipeline transport and for shipping. That is, the point at which transport cost by pipeline and by ship are equal. Transport distance is expressed in kilometers and is shown on the x-axis, while cost is shown on the y-axis. The graph is reproduced from Mallon (2013). In the following, we only operate with one transport cost estimate. The implicit assumption is therefore that cost are calculated such that the cost of transport by ship and pipeline break-even.

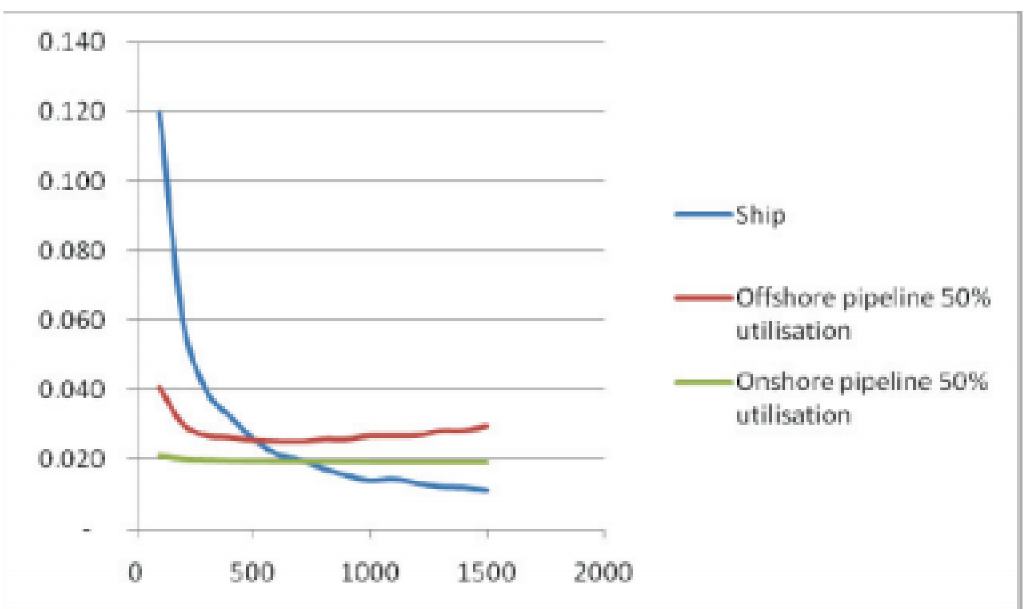

Figure 8: Transport cost expressed as EUR/tonne/km for pipelines at 50% capacity

When assessing cost, we adopt the same general approach as in the IPCC “Special

Report on Carbon Dioxide Capture and Storage" (IPCC, 2005) by inspecting the cost of CO_2 avoided. This is done by comparing a reference plant without CCS to a power plant with installed CCS. In order to do so, it is necessary to define the typical plant performance measure. This defines the plant capacity factor[8], power output and emissions rate for a typical design of a thermal[9] power plant. Table 1 summarizes the plant performance measures applied in this thesis. The evaluated parameters describes the levelized values during the lifetime cycle of a power plant. That is, the parameters are assumed to be constant during the entire lifecycle of the plant.

Plant performance measures are from Rubin et al. (2015), and are shown in the third column of table 1. Rubin et al. assess the results of recent reports in which the cost for carbon capture and storage is analyzed[10], and provides an updated version of the cost estimates in the IPCC Special Report on Carbon Dioxide Capture and Storage. As shown in the table, the reference plant design is 600 MW, which is the energy produced of a thermal power plant working at maximum capacity (i.e. 100%). However, due to heat loss and other inefficiencies in production, actual hourly energy output is lower. Actual power output equals 516 MWh, and is found by multiplying the plant capacity factor with reference plant design. Column 4 presents output per MWh.

[8]Ratio of net electricity generated to the energy that could have been generated at continuous full-power operation during the same period

[9]Power plant in which electric energy is generated by converting heat energy

[10]Specifically, the paper assesses the results of: USDOE (2010), USDOE (2013), GCCSI (2011), EPRI (2013), IEA GHG (2014) and ZEP (2011)

Term	Definition	Estimate from Rubin	Output per MWh
Reference plant design	Net plant capacity (MW)	600 MW	516
Plant capacity factor (%)	Ratio of net electricity generated to the energy that could have been generated at continuous full-power operation during the same period.	86	
Production hours	Average hours during analyzed production (5 years)	43830	1
Emission rate trad. plant	Emitted tons of CO_2(tCO2/MWh)	0,816	0,816
Emissions rate w/CCS	Emitted tons CO_2 per MWh produced	0	0
CO_2 captured	Tons of CO_2 captured		0,816

Table 1: Plant performance measures

Term	Definition	Estimate	Cost per MWh
Carbon tax ($)	Carbon tax paid by ref. plant	100/tCO_2	81,600
Cost unabated. power plant, ω^U ($)	Total cost of reference fossil fuel plant. Equal to the sum of fixed investment cost and variable cost ($/MWh)	89,800	89,800
Cost CCS power plant, ω^A ($)	Cost of power plant with CCS. Equal to sum of fixed investment cost and variable costs ($/MWh)	163,600	163,600
Fixed entry cost, f^A ($)	Fixed costs of constructing the pipeline system	4,203/tCO_2	3,430
Cost of storage of CO_2 ($)	Cost of storage in an offshore saline formation	12/tCO_2	9,792
Transport cost, t^A ($)		4,850	3,958

Table 2: Plant cost measures

Table 2 describes the plant cost measures applied in this thesis. The cost estimates are calculated for a power plant with plant performance measures as described in table 1. The cost estimates are expressed in constant dollars under the assumption that all values levelized. That is, costs are equal to the first-year cost of electricity generation, which are assumed to remain constant over a plant´s life-cycle. In table 2, the cost estimates of power plants with CCS and traditional power plants are from US EIA (2015), while storage and transport costs are from Rubin et al. (2015). These are summarized in the third column. Both are detailed studies published by governmental and well-known engineering firms in the power industry involved in the assessment of CCS and power plant technologies. The values have been recalculated in order to fit the power plant specifications. Finally, column four presents cost per MWh.

The hourly captured volume of CO_2 is equal to 421 tons. This is slightly higher than the captured volume of CO_2 reported in Rubin et al. (2015). They find that a pre-combustion CCS power plant captures an hourly volume of 365 tons of CO_2, which equal a capture rate of 90 %. The higher reported captured estimates in the present thesis is a result of the simplifying assumption of a zero-emission rate for CCS plant.

When determining the realized carbon tax, we apply IPCC´s estimated carbon price for 2030, which equals 100 $ per ton CO_2 emitted (IPCC, 2014). It is however important to note that this carbon tax is subject to uncertainty. The carbon tax needed to reach the 2DS could be both higher and lower than the estimate proposed by the IPCC. As the carbon tax estimate will have a decisive influence on our results, it is important to keep this in mind when analyzing the results of the simulations. However, to simplify, we assume that this carbon tax equals the marginal damage of emissions per ton CO_2. The carbon tax paid per MWh is found by multiplying the carbon tax with emitted tons of CO_2 per MWh produced, and is listed in column 5.

The cost facing an owner of an unabated power plant equals the sum of investment and marginal costs (i.e. ω^U) in table 2. This yields a cost estimate of 89,8 $ per MWh produced (EIA 2015). In addition to the power plant cost, the producer has to pay the carbon tax.

Total cost of a CCS power plant (i.e. ω^A) is calculated assuming an energy penalty of 23 % and an additional investment cost of 61,1 %. This yields a total cost of 163,6 $ per MWh produced (EIA 2015). In addition, a producer has to pay the cost of transport and storage of the captured CO_2. Remember that this was assumed to equal the cost of storage, c^A plus the average transport costs $\frac{5t^A}{4n^A}$.[11] As storage costs, we use the cost estimate from Rubin (2015), which estimates a storage cost of 12 \$/tCO_2. Rubin finds that transport cost of an offshore pipeline equals 7 \$/tCO_2 transported, which equals 5,712 \$/Mwh. However, as average transport cost in this model is determined both by the transport cost to each terminal, and the transport of CO_2 via pipeline, we cannot directly use Rubin´s estimate. As a solution, t^A is calibrated such that $\frac{5t^A}{4n^A}$ in the high equilibrium equals the transport cost reported in Rubin et al. (2015).[12] This was done using iteration. This gives $t^A = 4,850$ \$/tCO_2 captured, or equivalently $t^A = 3,958$ \$ per MWh. Then the fixed cost f^A can be found by inserting for the estimates in equation (4) and solving for f^A. This gives that the fixed costs of constructing the pipeline system are equal to 4,203/tCO_2, which translates into 3,430\$/MWh.

As for the carbon tax, it is important to note that cost regarding the CCS supply chain is subject to a significant uncertainty. Reported cost estimates for CCS technologies vary significantly. Some of this variation stems from actual cost differences or technological uncertainty, while some stems from differences in underlying assumptions and applied methodologies which vary significantly across studies. Thus, it is important to interpret the results with care.

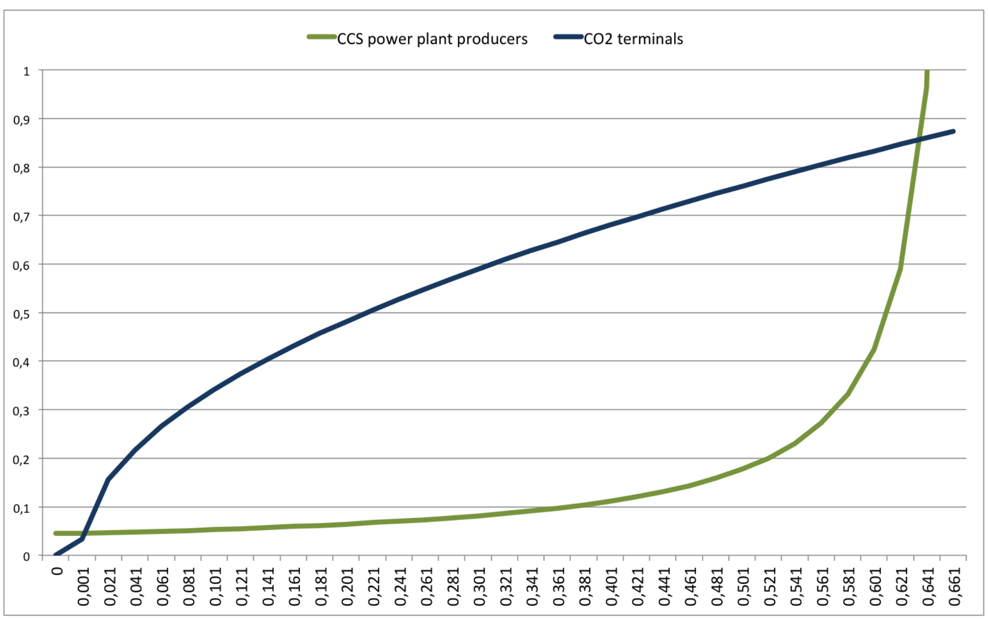

Figure 9: Equilibria

[11]This also includes $\frac{t^A}{4n^A}$, the transport cost to the storage site that the producer make up to the storage provider

[12]The terminal coverage in the high equilibrium equals $n^A = 0,86$

Figure 9 shows the numerical simulation when using the estimates in table 1 and table 2. The market share of abated power plants is shown on the x-axis, while the y-axis shows the coverage of CO_2 terminals. The blue graph depicts the best response function of CO_2 terminals while the green graph depicts the best response function of CCS power plants producers. The simulation yields two possible equilibria; one in which CCS captures a low market share, and one in which CCS captures a high market share. In the low equilibrium, the CCS market share equals $q^A = 0,001$ and the terminal coverage equals $n^A = 0,034$, given that the market is normalized to 1. That is, if the entire power plant constitutes of 100 power plants, then CCS captures a zero-market share in the low equilibrium.[13]

As argued in section 6, n^A is the terminal coverage necessary to keep the market self-sustaining, and may be interpreted as the critical mass of CO_2 terminals. The simulation therefore suggests that the terminal coverage needed to tip the energy market in favor of CCS is very low.

In the high equilibrium, $q^A = 0,641$ and $n^A = 0,86$. Again, if for simplicity, the entire energy sector constitutes of 100 power plants, 64 of which will be CCS power plants, and there will be 8 CO_2 terminals.[14]

7.1 The existence of lock-in

This section analyzes the existence of lock-in in the energy sector. Recall that Unruh (2000) argued that society suffers from carbon lock-in as a result of a process of path-dependent increasing returns to scale in technological and institutional co-evolution. Furthermore, he argued that this path dependence inhibits proper diffusion of environmental friendly technologies, "despite their apparent environmental and economic advantages". If this is so, carbon lock-in may inhibit proper diffusion of carbon capture and storage technology.

Greaker and Heggedal (2010), define lock-in as "a situation in which two or more market equilibria exist, and in which the realized equilibrium is welfare inferior to the unrealized equilibrium". Adopting their definition, there will be lock-in in the market for CCS if the following conditions are satisfied: (1) the market must settle on an equilibrium with

[13]Calculation gives 0,1 CCS power plants, which is not possible.

[14]This follows from eq. (4): $n = \sqrt{\frac{3,958 \cdot q^A}{3,430}} \approx \sqrt{q^A} \approx 8$

lower realized market-share of CCS power plants, and (2) the realized equilibrium is welfare inferior to the unrealized equilibrium with a high market share of CCS.

The definition of lock-in may be inspected by analyzing figure 10. Using the definition of lock-in by Greaker and Heggedal (2010), there will be lock-in in the energy sector if CCS captures *either* a high or a low market share which is welfare inferior to another allocation. Furthermore, the energy market will suffer from *excess inertia* if the low equilibrium is realized, but the equilibrium in which CCS captures a high market share is welfare superior. In contrast, the energy market will suffer from *excess momentum* if the high equilibrium is realized, but the equilibrium in which CCS captures a low market share is welfare superior.

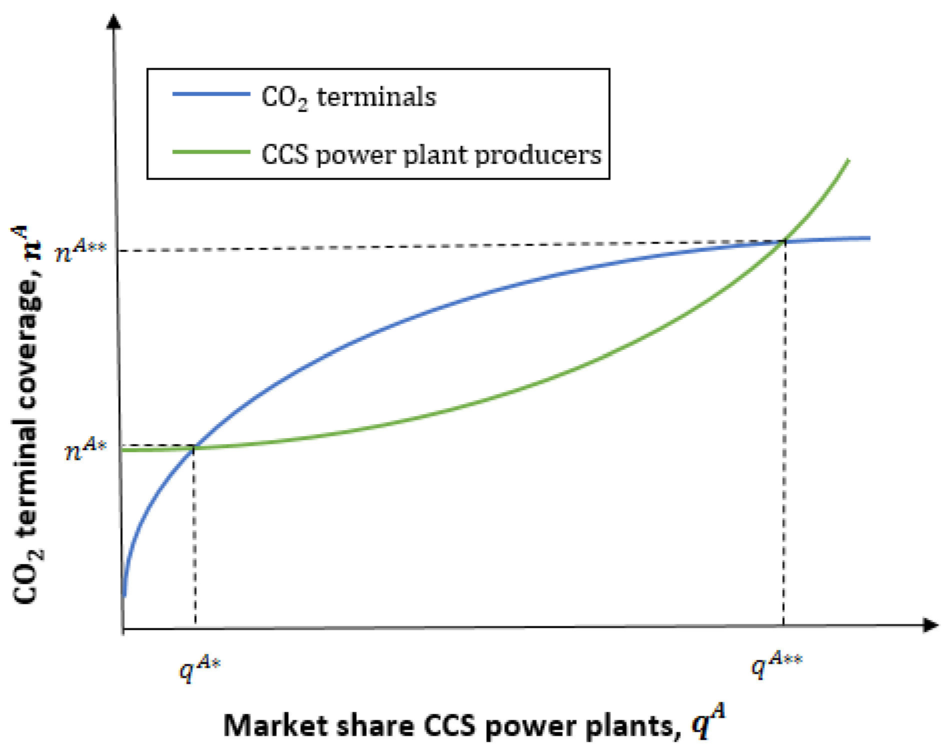

Figure 10: Equilibria and lock-in

Initially, the entire energy sector constitutes of unabated power plants. As producers maximize profits, they will choose to invest in a CCS plant rather than in an unabated plant if this is profit maximizing based on their *belief* of the carbon tax. As producers invests in CCS power plants, demand for CO_2 transport and storage services increase.

This will attract CO_2 terminals. Entry of CO_2 terminals will not affect our welfare analysis as entry will continue until profit opportunities are exhausted. However, as more terminals enter, price competition increases, and as a consequence the markup each terminal may charge is reduced. As a result of reduced costs, CCS power plants become more attractive, leading to increased investments in CCS.

The environmental cost of emissions is important to our analysis of whether the market suffers from lock-in. From an environmental perspective, there may be great benefits from extensive adoption of CCS. As described in section 3, UNPCC and other major intergovernmental agencies argue that vast CCS adoption is necessary to limit global warming to 2 degrees celsius.

Social welfare is defined by the sum of consumer- and producer surplus. In the present model, consumers are not affected by the entry of CCS power plants. This follows from the assumption that each power plant producer must either invest in an abated or in an unabated facility, and that the capacity factor of a CCS power plant and an unabated power plant are equal. Consequently, the energy supply is unaffected by investments in CCS. As supply is given, the plant decision will not affect the price. Since the price of electricity is unaffected, consumer surplus is unaffected as well. Social welfare is thus given by the producer surplus of those investing in an unabated facility, plus the producer surplus of those investing in a CCS facility, plus the avoided environmental costs due to investments in CCS.

In the present model, some producers expect a carbon tax which is higher than $100\$/tCO_2$, while other producers expect a carbon tax which is lower than $100\$/tCO_2$. Again, as a simplification, the realized carbon tax is assumed to equal the average expected carbon tax in the benchmark model, which equals $100\$/tCO_2$. Furthermore, the marginal damage of emissions is internalized by the assumption that the realized tax is equal to the marginal damage of emissions. This assumption is made as we wish to isolate the effect of indirect network effects on adoption of CCS by internalizing the environmental externality. As a result, the definition of lock-in in this thesis is very simple: CCS is subject to lock-in if the carbon tax is sufficiently high, and the profits of an abated power plant are higher than the profits of an unabated power plant, but the energy sector still ends up in an equilibrium in which CCS captures a low market share.

As the gross revenue of an unabated facility equals the gross revenue of an abated facility[15], which type of facility that has higher profits can be assessed by comparing

[15]Formally, this follows from the assumption $\Gamma^A = \Gamma^U$

the costs of the respective plants. The costs of an unabated power plant is given by the sum of power plant costs and the carbon tax. This gives:

$$C^U = \omega^U + \lambda_x \tau$$

Inserting for the respective cost estimates from table 2 yields:

$$C^U = 89,9 + 81,6 = 171,50$$

Note that estimates above express costs per MWh. Thus, a carbon tax equal to 100 $\$/tCO_2$ translates into a carbon tax of 81,6$/MWh. The cost of an abated CCS facility is given by the following equation, which states that costs equal the sum of power plant costs, average transport cost and the cost of storage:

$$C^A = \omega^A + \frac{5t^A}{4n^A} + c^A$$

Inserting for the respective cost estimates from table 2 yields:

$$C^A = 163,6 + 5,712 + 9,792 = 179,104$$

Given our cost estimates, profits of a CCS power plant are less than the profits of an unabated power plant. As marginal damage of emissions is internalized through the carbon tax, consumers are unaffected and producer surplus is highest under investments in unabated power plants, social welfare is maximized if all producers invest in unabated power plants and pay the carbon tax. Thus, there is no evidence of excess inertia in the market for carbon capture and storage. In addition, it is possible that the model produces excess momentum! This is a new result compared to the model by Greaker and Heggedal (2010). As illustrated by the simulation in Figure 9, there are two possible equilibria which feature a positive CCS market share for the given set of cost estimates. Thus, there will be excess momentum if *any* of the equilibria featuring a positive market share of CCS is realized. Consequently, given the present cost estimates, there is no justification for government intervention in the market for carbon capture and storage.

As apparent from above, the carbon tax will have a decisive influence on whether the CCS market suffers from lock-in. Furthermore, as the cost difference between abated and unabated plants is relatively small, it might be interesting to find the carbon tax which makes the costs of a CCS facility equal to the cost of an unabated facility. The cost per MWh is equal for unabated and abated power plants when the carbon tax equals 89,20$/MWh. This is the equivalent of a carbon tax equal to 109,31$/t$CO_2$. Consequently, any carbon tax rate higher than 109,31$/t$CO_2$ will imply that the result above is reversed. This shows that our results is very sensitive to changes in cost estimates, such that the results should be interpreted with care.

8 The effects of too low carbon tax rate expectations among producers

The previous analysis assumed that producers (on average) expected that the carbon tax was equal to the 2DS carbon tax rate of 100\$/tCO_2. This section relaxes this assumption by analyzing the case in which producers believe that the carbon tax will be lower than the 2DS carbon tax rate. Specifically, equilibria are calculated assuming that $\theta = 1$. That is, the producers (on average) expect a carbon tax rate equal to 50\$/tCO_2, or equivalently 40,8 \$/MWh.

There may be several reasons why producers expect a carbon tax which is lower than the 2DS carbon tax rate. Past experience with international climate agreements such as the Kyoto Protocol have illustrated the challenges of international collaboration on emission reduction. In particular, producers may not believe that it will be politically feasible to commit to a 100 \$/tCO_2 carbon tax within the time period 2025-2030.

Figure 11 illustrates the numerical simulation in which producers have too low expectations regarding the carbon tax rate, i.e. $\theta = 1$. As before, the realized carbon tax is assumed to equal the 2DS carbon tax rate of 100\$/tCO_2.

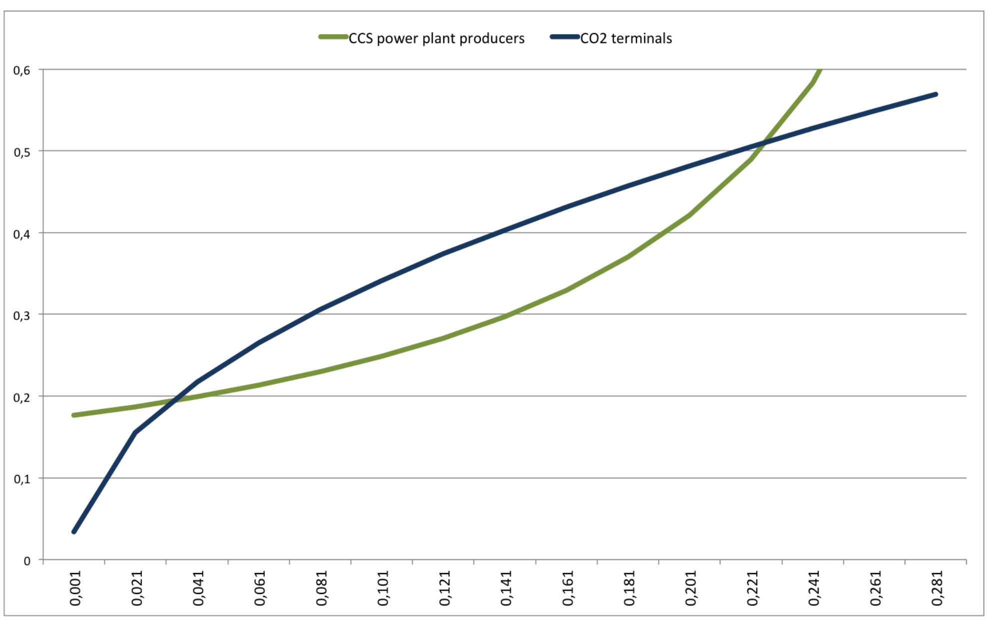

Figure 11: Equilibria when producers have too low expectations regarding carbon taxes, ($\theta = 1$)

As illustrated in Figure 11, with current costs, the interval in which CCS captures a positive market share decreases when producers have incorrect expectations regarding the carbon tax. In response to lowered carbon tax expectations among producers, the best response curve of the CCS producers shifts upwards in the diagram. For any given coverage of CO_2 terminals, investments in CCS power plants is therefore lower. This is because the reduced carbon tax expectations make the producers believe profits will be maximized when they invest in an unabated power plant. The simulation suggests that $q^A = 0,241$ and $n^A = 0,527$ in the high equilibrium. That is, if the entire energy sector constitutes of 100 power plants, 24 of these will be CCS power plants, and there will be four or five terminals. [16] In the low equilibrium, $q^A = 0,041$ and $n^A = 0,218$. Again, if if the entire energy sector constitutes of 100 power plants, four of these will be CCS power plants, and there will be two terminals. CCS thus captures a higher market share in the low equilibrium. The intuition behind this result is that the critical mass which is required to tip the market in favor of CCS is now higher. It is therefore more difficult to reach the equilibrium in which CCS captures the high market share. This is a direct result of the producers lowered expectations.

8.1 Low expected carbon tax and lock-in

As the realized tax rate is still 100 $/t$CO_2$, the expressions for social welfare is the same as in the benchmark model, restated here for reference:

$$C^U = 89,900 + 81,600 = 171,500$$

$$C^A = 163,600 + 5,712 + 9,792 = 179,104$$

The welfare of the consumers is still unaffected. The effect on welfare may therefore be inspected by analyzing the effect on the producer surplus. With current costs, the costs of an unabated power plant are still less than than the cost of an abated power plant, such that social welfare is maximized if producers invest in unabated power plants and pay the carbon tax. The numerical simulation in figure 11 show that the CCS market share is significantly lower than in the benchmark model, implying that social welfare is higher. That social welfare is higher when producers have "wrong" expectations

[16]This follows from eq. (4): $n = \sqrt{\frac{3,958 \cdot q^A}{3,430}} \approx \sqrt{q^A} \approx 4,9$

regarding carbon taxes may seem like a counterintuitive result. However, it is a result of the assumptions that the marginal damage of emissions is internalized through the carbon tax and consumers are unaffected such that the producer surplus is the only determinator of social welfare.

The realized equilibria still features excess momentum such that there is no justification for government intervention in support for CCS.

9 The effect of technological development in carbon capture

This section inspects the effects of technological development in the carbon capture chain. Specifically, it assesses the effects of reducing the operating costs, or "energy penalty" of a CCS plant. At present, the energy penalty associated with CCS power plants is significant. A substantial amount of heat and energy is required to separate CO_2 from the other gases (mainly water vapor and nitrogen) and compressing it for transport. This will in turn reduce the net energy output of a plant. As experience with CCS plants increase and the technology becomes more commercialized, this added cost will likely be reduced. For instance, extensive research is already conducted to find more efficient ways to separate the CO_2 or to redirect some of the heat which otherwise would be wasted from CO_2 compression.

The analysis in sections 7 and 8 were simulated assuming a 23 % added energy penalty of abated power plants. In the following, the numerical solution is simulated under the assumption that there is technological progress such that the energy penalty of an abated power plant is reduced to 10 %. Reducing the energy penalty increases the profitability of CCS power plants. One may therefore expect that this would increase demand for abated power plants for any given coverage of CO_2 terminals by creating a negative shift in the best response curve of the CCS power plants.

Figure 12 show the equilibria when the energy penalty of CCS power plants is reduced to 10 %. In the low equilibrium, the market share of CCS is equal to $q^A = 0,001$ and the terminal coverage is equal to $n^A = 0,034$. This is the same value as in the simulation in section 7. Reducing the energy penalty has therefore an unnoticeable impact on the low equilibrium. In the high equilibrium, $q^A = 0,661$ and $n^A = 0,873$. If, for simplicity, the entire energy sector constitutes of 100 power plants, 66 of these would be CCS power plants, and there would be eight terminals. This is higher than the high equilibrium featured in the simulation in section 7. Abated power plants therefore capture a slightly higher market share when reducing the energy penalty. In sum however, the numerical simulation suggests that reducing the energy penalty has only a small effect on the realized equilibria.

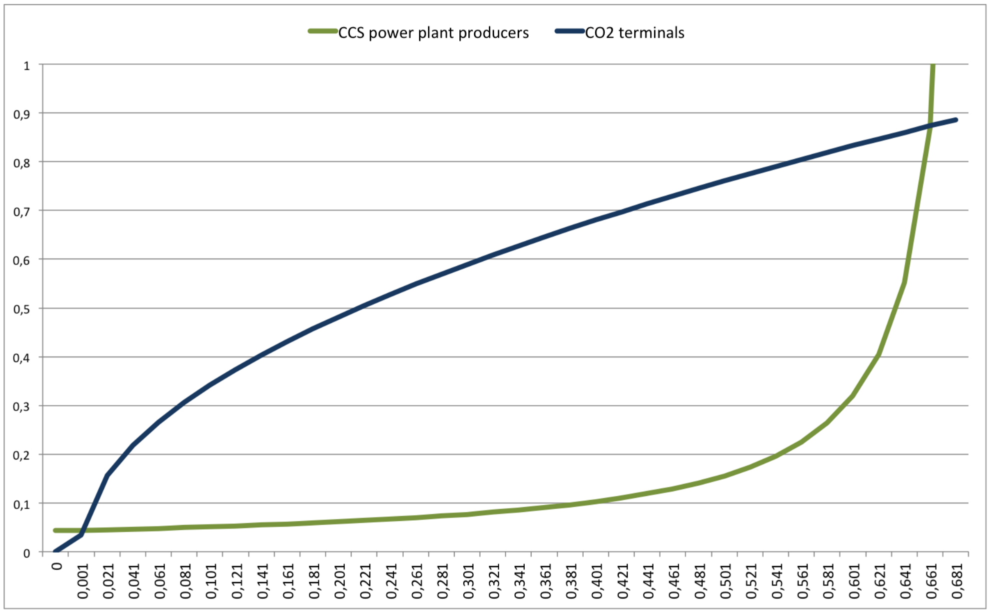

Figure 12: Market equilibrium with 10 % added energy penalty of CCS

9.1 Technological development and lock-in

As technological development will increase the profitability of an abated power plant, social welfare needs to be recalculated. Again, as gross revenue of an unabated facility equals the gross revenue of an abated facility, profitability is assessed by comparing the costs of the respective plants. The costs of an unabated power plant equal the power plant cost plus the carbon tax, given by the following equation:

$$C^U = \omega^U + \lambda_x \tau$$

As the profitability of unabated power plants is unaffected, inserting for the respective cost estimates from table 2 yields the same cost estimate as before:

$$C^U = 89,9 + 81,6 = 171,50$$

The cost of a CCS facility is given by power plant costs, expected transport cost and the cost of storage. This gives the following equation:

$$C^A = \omega^A + \frac{5t^A}{4n^A} + c^A$$

Lowering the energy penalty by 10 % yields $\omega^A = 129,64$. Inserting for the the reduced value of ω^A gives:

$$C^A = 129,64 + 5,712 + 9,792 = 145,144$$

The calculation above shows that abated plants are now more profitable than unabated power plants. Reducing the energy penalty of abated power plants therefore reverses the results of section 7 and 8. As before, consumers are unaffected and marginal damage of emissions are internalized through the carbon tax. Social welfare is therefore defined by the producer surplus. As producer surplus is maximized when producers invest in CCS, social welfare is maximized if producers invest in CCS power plants. The numerical simulation in Figure 11, in contrast, illustrated that the market share of CCS is nearly unaffected by the reduction in energy penalty. As the welfare gains of investing in CCS has increased, while the realized CCS market share is nearly unaffected, there is now evidence of lock-in in the market for carbon capture and storage if the CCS captures a small market share. Thus, government intervention may now be justified.

The government could try to increase the market share of CCS power plants in several ways. Firstly, the government could support the market through subsidies. In addition, the government could try to increase the CCS market share by showing that they commit to the technology. The Norwegian Government has applied both methods when trying to increase investments in CCS.

Note that this equilibrium is second best. As terminals enter until profit opportunities are exhausted, there is excessive entry in the Salop model (Tirole 1988). A social planner, in contrast, would allow entry of terminals by minimizing the transport and fixed costs. Thus, when analyzing whether the market is subject to lock-in, the present analysis compares two second best allocations. Therefore it is possible that there exist another allocation which Pareto dominates both equilibria. This is inspected in section 11.

10 The effect of too low expectations regarding carbon taxes combined with technological development

This section inspects the effect of reducing the energy penalty associated with CCS when producers believe that the carbon tax rate is lower than the realized carbon tax rate. In the following, the numerical simulation is modeled assuming an energy penalty of 10 % for power plants with CCS and $\theta = 1$. As before, the realized carbon tax is assumed to equal 100\$/tCO_2.

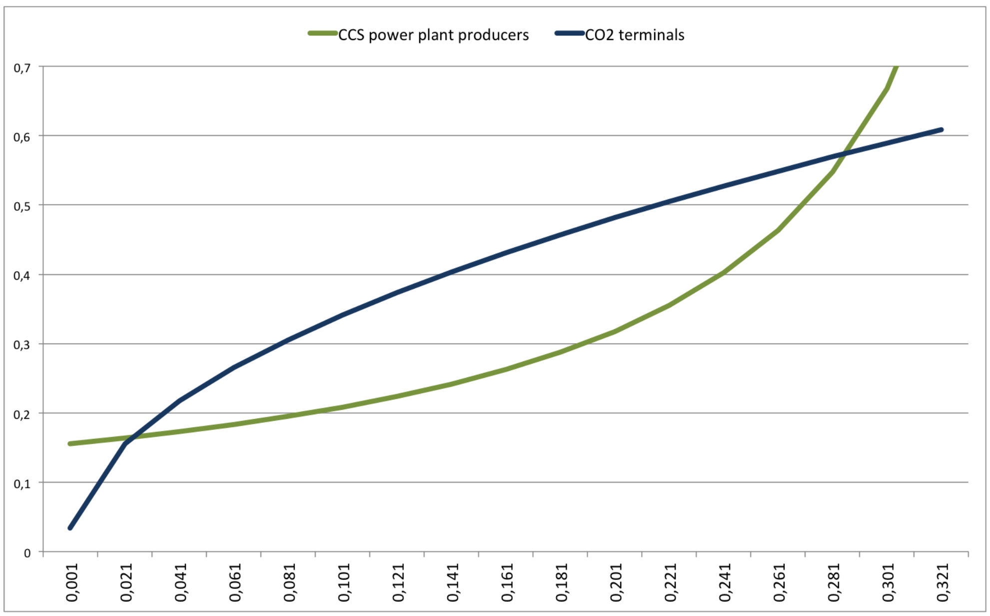

Figure 13: Equilibria with 10 % energy penalty when producers have to low expectations ($\theta = 1$)

Figure 13 illustrates the numerical simulation. The high equilibrium now yields $q^A = 0,281$. and $n^A = 0,569$. If, as before, the energy sector constitutes of 100 power plants, 28 of these would be CCS power plants, and there will be five terminals. In addition, the low equilibrium now yields a CO_2 terminal coverage equal to n^A = 0,156 and $q^A = 0,021$. Reducing the energy penalty while assuming that producers have too low expectations regarding carbon taxes has two opposite effects. Reducing the energy penalty shifts the best response curve of CCS producers down in the diagram; The operating cost of a CCS power plant is lower for any given level of CO_2 terminal, which in turn leads to a higher investments in CCS. However, as illustrated by the discussion in section 8, this effect is small. In addition, lowered carbon tax expectations imply that the producers believe that unabated power plants are more profitable than abated power plants. This shifts the best response curve of the producers upwards in the diagram, leading to a lowered market share of CCS in the high equilibrium and a higher CO_2 terminal coverage needed to tip the market in favor of CCS.

10.1 Lock-in

As the reduction in energy penalty is assumed to be the same as in section 9, the calculations for social welfare are valid here as well. The total cost estimates for unabated and abated power plants, respectively, are restated here for reference:

$$C^U = 89,9 + 81,6 = 171,50$$

$$C^A = 129,64 + 5,712 + 9,792 = 145,144$$

Again, it is clear from the cost estimates above that CCS is the most cost efficient option, as the total costs of energy production per MWh for an abated plant is significantly lower than the total cost of energy production per MWh for an unabated plant. Thus, social welfare would be maximized if producers invested in CCS power plants. The numerical simulation, in contrast, suggests that the market share of CCS in the high equilibria only yields a market share of CCS equal to $q^A = 0,281$ That is, if the entire energy sector constitutes of 100 power plants, 28 of which will be CCS power plants, and there will be five terminals. Meanwhile, the terminal coverage needed to keep the market self sustaining has increased to n^A = 0,156 which gives $q^A = 0,021$. Thus, if there is a 100 power plants in the energy sector, there will be only two CCS power plants, and one CO_2 terminal! As a result, there is now significant excess inertia in the market for carbon capture and storage if CCS only captures a low market share. The high equilibrium also gives a too low CCS market share, but this is because the agents have incorrect beliefs regarding the carbon tax. Thus, the present model illustrates that there is significant welfare loss due to the incorrect expectations amongst producers and that excess inertia may arise.

Note that the simulation yields results in line with Greaker and Midtømme (2016) which find that a Pigouvian tax rate may not be sufficient to ensure diffusion of clean technology.

11 Correcting for the market failure in the Salop circle

As mentioned, the equilibrium allocation described in section 9 and 10 are second best. The CO_2 terminals enter the market until profit opportunities are exhausted. That is, until the zero-profit condition is satisfied. The equilibrium solutions therefore suffers from excess entry of CO_2 terminals. There is therefore possible that there exist another allocation which Pareto dominates both equilibria. In the following, the equilibrium defined by free-entry is compared to the equilibrium chosen by a social planner. The social planner minimizes the sum of fixed costs of building the pipeline and the transport cost of the producers:

$$\min \left[nf + \frac{t}{4n} \right] \tag{11}$$

This gives the following number of firms as a function of fixed cost and transport costs:

$$n^* = \frac{1}{2}\sqrt{\frac{t}{f}}$$

Inserting for t and f from table 2 gives:

$$n^* = 0,537$$

The comparison of cost in section 9.1 showed that social welfare was highest if all producers invested in CCS power plants as profits where then higher. The socially optimal allocation is therefore defined by CCS power plant capturing the entire energy sector, and $n^* = 0,537$. That is, if the entire energy sector constitutes of 100 power plants, all of which will be CCS power plants, and there will be 10 terminals. This result illustrates that there is indeed an allocation which is welfare superior to the allocations described in sections 9 and 10. Again, it is however important to note that this result rest on our cost estimates which are subject to significant uncertainty. Thus, the *actual* socially optimal allocation may differ from this one.

12 Conclusion

As mentioned in the introduction, as part of the Norwegian Government's CCS strategy, Gassnova awarded contracts to Klemetsrudanlegget, Norcem and Yara on April 19th. These were granted financial support for continued studies on full-scale carbon capture at their respective facilities. The goal is to complement carbon capture at these facilities with transport by ship to an on-shore facility which will transport the captured CO_2 by pipeline to an offshore storage site in the North Sea. This thesis has highlighted some key aspects with this regard.

The results in this thesis indicate that the steps moving CCS to commercialization depend critically on the producers' belief regarding the carbon tax and reducing the additional cost of CCS beyond current cost levels. The simulation in the benchmark model provided no evidence of excess inertia. As producer surplus was higher if all producers invested in unabated power plants, social welfare was maximized if unabated power plants captured the entire energy sector. In addition, excess momentum was possible if any of the equilibria in which CCS captured a positive market share were realized. The scenario in which producers had incorrect expectations regarding the carbon tax with current costs also gave no evidence of excess inertia, and gave a significant reduction in the equilibria in which CCS captured a positive market share. The simulations, however, suggested that the results were highly sensitive to changes in cost.

Reducing the energy penalty associated with the operation of CCS power plants reversed the results from above, and suggested that the energy sector suffered from excess inertia. These results arose as the reduced energy penalty improved cost efficiency by so much that the profitability was highest for CCS power plants. As a result, social welfare was maximized if all producers invested in CCS power plants. The energy sector therefore suffered from excess inertia if the energy sector settled on the equilibrium in which CCS captured a small market share. In terms of implications for public policy, this result supports the strategy of Norwegian Government which argue that the energy sector constitutes of many, independent agents, the market will unlikely produce the efficient allocation.

Finally, when analyzing the effect of incorrect carbon tax expectations and a reduced energy penalty, the simulation suggested that the energy sector suffered from significant excess inertia. Reducing the energy penalty when producers had incorrect expectations had two opposite effects. However, as the effect of incorrect expectations was stronger than the effect of a reduced energy penalty, it was less likely that CCS diffused into the energy sector. This increased the CO2 terminal coverage required to ensure a self-sustaining market for CCS, thus making it more difficult to reach the high equilibrium. In addition, it significantly reduced the CCS market share in the high equilibrium. The results of this simulation also illustrated the sensitivity of the commercialization of CCS to the beliefs of the producers, and highlighted the importance of establishing sufficiently high expectations regarding carbon taxes.

A key message from the results in this thesis is that even if the market for CCS does not suffer from excess inertia in all of the analyzed scenarios, the simulations suggest that one will with small changes, such as only a small reduction in costs or a slightly higher carbon tax, end up with the opposite result. In addition, when correcting for the market failure in the Salop model, the CCS market share in the high equilibrium exceeded the CCS market share produced by the market. Thus, given our results, government intervention may be justified. However, the sensitivity of the results to changes in cost estimates combined with the general uncertainty regarding CCS cost estimates suggest that the results should be interpreted with much care.

One important feature of the discussion on CCS has not been analyzed in this thesis. This is the effect of using captured CO_2 for the purpose of EOR, which has gained increased attention as a possible method to incorporate CCS in the North Sea. In a recent article, Pham and Halland (2017) argue that "CO_2 for EOR can create a market for CO_2 that improves the economics of CCS and it can be combined with permanent storage of CO_2." Furthermore, a recent study executed by the Norwegian Petroleum directorate finds several reservoirs in the Norwegian North Sea which show significant potential for EOR in terms of depth, temperature and pressure (Pham and Halland, 2017). Analyzing the effects of EOR in the present model would be straightforward, and could be done by using a credit, (i.e. negative cost) for CCS power plants. Doing so would substantially improve the cost effectiveness of CCS, and make it the profit maximizing option. It would, however, also make the economics of CCS highly sensitive to changes in the oil price. As a result, we have chosen to exclude EOR. This is also done because, as argued in Section 2, it is disputable whether EOR can be considered a climate mitigating option.

In terms of implications for future research, the thesis has touched upon two topics. First, costs are modeled as independent of market size. However, learning effects may also play a role in the deployment of CCS. Costs may decrease beyond what is modeled in this thesis as the accumulated capacity of CCS increases. This would likely increase the likelihood of excess inertia. One possible way to make the model more realistic could therefore be to let costs depend on the accumulated capacity of CCS. Secondly, the existence of multiple equilibria in this thesis highlights the importance of coordination in the CCS market. Timing could arguably also be of importance. As argued in Section 2, smaller profit margins and uncertain future market conditions create a barrier to investments in CCS. The model, however, is very simple in the sense that it features a one-stage game in which producers and terminals act simultaneously. It could therefore be interesting to allow for sequential entry by CO_2 terminals and CCS power plants, and see if this alters the results. We leave this for future research.

References

[1] IPCC(2014a), "Climate Change 2014 - Synthesis Report," Technical report, IPCC, uRL: https://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf, Accessed February 12th 2017, 2014

[2] IPCC(2014b), "IPCC 2014 Mitigation of Climate Change - Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change," Technical report, Intergovernmental Panel on Climate Change, 2014

[3] KreyV., Luderer G., Kriegler E. (2014), "Getting from here to there - energy technology transformation paths in the EMF27 scenarioes," *Climatic Change*, pp. 362–369, 2014

[4] ZEP, (2014), "Business Models for commercial CO2 transport and storage - Delivering large-scale CCS in Europe by 2030," Technical report, Zero Emissions Platform, uRL: https://www.thecrownestate.co.uk/media/389780/ei-business-models-for-commercial-co2-transport-and-storage-zep.pdf, 2014

[5] IEA, (2016), "Energy Technology Perspectives 2016," Technical report, IEA, 2016

[6] OsloEconomics, (2016), "Kvalitetssikring (KS1) av KVU om demonstrasjon av fullskala fangst, transport og lagring av CO2," Technical Report D014a, Oslo Economics, accessed February 12th 2017, 2016

[7] Greaker M., Midttomme K., (2016), "Network effects and environmental externalities: Do clean technologies suffer from excess inertia?" *Journal of Public Economics*, volume 143, pp. 27–38, accessed April 12th 2017, 2016

[8] Greaker M., Heggedal T.R.(2010), "Lock-In and the Transition to Hydrogen Cars: Should Governments Intervene?" *The BE Journal of Economic Analysis Policy*, volume 10, no. 1, ISSN 1935-1682, 2010

[9] Aakenes S., (2014), "From Moon-walking towards Moon-landing: How might CCS leave the Launch Pad," *CREE Working Paper 132014*, http://www.cree.uio.no/publications/2014_13/Commercial_barriers_master_thesis_Aakenes_Cl Accessed april 11th 2016, 2014

[10] Banks J. P., Boersma T., Goldthorpe W. (2017), “Challenges related to carbon transportation and storage - Showstoppers for CCS?” Technical report, GCSSI, 2017

[11] Brookings(2015), “Brookings Energy Security and Climate Initiative Coal in the 21st Century: FOSTERING LOW-CARBON ENERGY-Next Generation Policy to Commercialize CCS in the United States,” URL: https://www.brookings.edu/wp-content/uploads/2016/06/low_carbon_energy_ccs_banks_boersma_FINAL.pdf, accessed April 11th, 2015

[12] Blyth W., (2010), “The Economics of Transition in the Power Sector,” URL: https://www.iea.org/publications/freepublications/publication/economics_of_transition.pdf, Accessed April 11th 2017, 2010

[13] Lieberman M. B., Montgomery D. B. (1988), “First-Mover Advantages,” *Strategic Management Journal Special Issue Strategy Content Research*, volume 9, pp. 41–58, accessed April 11th 2017, 1988

[14] Greenpeace, (2017), “Carbon capture and storage a costly, risky distraction,” Accessed April 11th 2017

[15] Moore G., (1991), *Crossing the Chasm*, HarperBusiness, 1991

[16] Farrell J., Klemperer P. (2007), *Coordination and Lock-In: Competition with Switching Costs and Network Effects*, chapter 31, pp. 1967–2072, 2007

[17] Liebowitz S., Margolis S. (1995), “Path Dependence, Lock-In and history,” *Journal of Law Economics and Organization*, 1995

[18] Yu Z., Li S., Tong L. (2016), “Market dynamics and indirect network effects in electric vehicle diffusion,” *Transportation Research Part D Transport and Environment*, volume 47, pp. 336–356, 2016

[19] Caillaud B, Jullien B. (2003), “Chicken and egg: competition among intermedia-tion service providers,” *RAND Journal of Economics*, volume 34, no. 2, pp. 309–328, 2003

[20] Farrell J., Saloner G. (1985), “Standardization, compatibility and innovation,” *Rand Journal of Economics*, volume 16, no. 1, pp. 70–83, accessed April 12th 2017, 1985

[21] Farrell J., Saloner G. (1986), "Installed base and compatibility: Innovation, product preannouncements and predation," *The American Economic Review*, volume 76, no. 5, pp. 940–955, accessed February 7th 2017, 1986

[22] Unruh G., (2000), "Understanding carbon lock-in," *Energy Policy*, volume 28, pp. 817–830, ISSN 1935-1682, uRL: http://ac.els-cdn.com/S0301421500000707/1-s2.0-S0301421500000707-main.pdf?_tid=8f8cb8a0-1fa0-11e7-baad-00000aab0f27&acdnat=1492016192_0fbdbbf317eba628cba282e24ce4d9ea, Accessed May 9th, 2000

[23] Katz M., Shapiro C. (1986), "Technology Adoption in the Presence of Network Externalities," *Journal of Political Economy*, volume 94, no. 4, pp. 822–41, 1986

[24] Liebowitz S.J., Margolis S. E., (1994), "Network externality: An uncommen tragedy," *Journal of Economic Perspectives*, volume 8, no. 2, pp. 133–150, accessed February 7th 2017, 1994

[25] Greaker M., Golombek R., Rogeberg O. Aune F. (2009), "Carbon capture and storage technologies in the European power market," *SSB Discussion Paper*, uRL: http://www.ssb.no/a/publikasjoner/pdf/DP/dp603.pdf, accessed May 10., 2009

[26] Salop S., (1979), "Monopolistic Competition with Outside Goods," *The Bell Journal of Economics*, volume 10, no. 1, pp. 141–156, uRL: http://www.jstor.org/stable/3003323, Accessed March 12th 2017, 1979

[27] GCCSI, (2017b), "Case Study - The Sleipner Gas Field," URL: https://hub.globalccsinstitute.com/publications/carbon-dioxide-storage-geological-security-and-environmental-issues-case-study-sleipner-gas-field-norway/81-background, Accessed April 12th 2017

[28] Torp T., Christensen N.P. (1998), "Capture and reinjection of CO2 in a saline aquifer at Sleipner Field and the future potential of this technology. Dinner-debate with the Foundation EuropÃ©enne de l'Energie in Brussels on 2 June 1998." Accessed April 12th 2017, 1998

[29] MIT, (2016), "Sleipner Fact Sheet: Carbon Dioxide Capture and Storage Project," URL: https://sequestration.mit.edu/tools/projects/sleipner.html, Accessed April 18th 2017, 2016

[30] Statoil, (2017), "Fields and Platforms - Sleipner field," Accessed April 18th 2017, 2017

[31] Tirole J., Fudenberg D. (1991), *Game Theory*, MIT Press, ISBN 9780262061414, 1991

[32] Mallon W, Buit L., Wingerden J. Lemmens H Eldrup N. H. (2013), “Cost of CO2 transportation infrastructures,” *Energy Procedia*, volume 37, pp. 2969–2980, uRL: http://ac.els-cdn.com/S1876610213004268/1-s2.0-S1876610213004268-main.pdf?_tid=404907a4-21ac-11e7-9ad2-00000aab0f01&acdnat=1492241115_42850ddf7a937485e9f28a8973e32f58, Accessed April 15th 2017, 2013

[33] IPCC, (2005), “Carbon Dioxide Capture and Storage,” Technical report, IPCC, uRL: https://www.ipcc.ch/pdf/special-reports/srccs/srccs_wholereport.pdf, Accessed April 12th 2017, 2005

[34] Rubin E., Davison J., Herzog H. (2015), “The cost of CO2 capture and storage,” *International Journal of Greenhouse Gas Control*, volume 40, pp. 378–400, accessed April 1st 2017, 2015

[35] Tirole J., (1988), *The Theory of Industrial Organization*, The MIT Press, 1988

[36] GCCSI, (2017a), “Challenges related to carbon transportation and storage - Showstoppers for CCS?” , 2017

[37] Cabral L., (2011), “Dynamic price competition with network effects,” *Review of Economic Studies*, volume 78, pp. 83–111, accessed February 7th 2017, 2011

[38] Gassnova, (2016), “Mulighetsstudier av fullskala CO2-handtering i Norge,” Technical report, Gassnova, accessed February 10th 2017

[39] Katz M. L., Shapiro C. (1985), “Network Externalities, Competition and Compatibility,” *The American Economic Review*, volume 75, no. 3, pp. 424–440, uRL: http://www.jstor.org/stable/1814809, Accessed April 17th 2017, 1985

[40] EIA, (2016), “Energy Technology Perspectives 2016,” Technical report, International Energy Agency, 2016

[41] IEA, (2015), “Energy Technology Perspectives 2015 - Mobilising Innovation to Accelerate Climate Action,” Technical report, International Energy Agency, 2015

[42] Torp T., Christensen, N.P. (1998), “Capture and reinjection of CO2 in a saline aquifer at Sleipner Field and the future potential of this technology. Dinner-debate

with the Foundation EuropÃ©enne de l'Energie in Brussels on 2 June 1998." Accessed April 18th 2017, 1998

[43] GCSSI, (2016), "Sleipner CO2 storage project," URL: https://www.globalccsinstitute.com/projects/sleipnerAccessed April 18th 2017, 2016

[44] Wikipedia, (2017), "Base Load," Accessed April 18th 2017

[45] Pham V., Halland E., (2017), "Perspective of CO2 for Storage and Enhanced Oil Recovery (EOR) in Norwegian North Sea," *Energy Procedia*, 2017

[46] IEA, (2017), "World Energy Outlook -Scenarios and projections," URL: https://www.iea.org/publications/scenariosandprojections/