Master thesis for the Master of Philosophy in Economics degree

Carbon capture and storage at Mongstad

- *an optimal contract for the Norwegian government?*

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Preface

When I had my first course in microeconomics, I could not understand how economists could possibly have something to say when it came to environmental issues. After some years of study, I realized that environmental economics was actually a field that really captured my interest.

Thanks to Vitenskapsbutikken, I got in contact with CICERO – Center for International Climate and Environmental Research - Oslo, and elaborated my working hypothesis in collaboration with them. The staff at CICERO has been a unique source of inspiration and information – thank you all!

I would also like to give a large thanks to my supervisor, Cathrine Hagem at Statistics Norway, for encouraging comments and very quick responses to my e-mails.

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Last, but not least, I have to express gratitude to my fellow students at Blindern, for making the time spent there unforgettable. They have, together with my other friends and family encouraged and supported me all the way through my studies.

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1. Introduction

"*The Norwegian government and Statoil have undertaken an agreement to establish the world's largest full-scale CO_2 capture and storage (CCS) project in conjunction with the projected combined heat and power plant at Mongstad.*"

Press release, Ministry of Petroleum and Energy, 12. October 2006

This project, the importance of which the government compared to landing on the moon, has been heavily debated in recent months. Removing and storing the carbon dioxide (CO_2) from gas-fired power plants represents a much cleaner way to produce electricity and make use of fossil fuels. This is a new and costly technology. There is a lot of uncertainty associated with these costs, and as it turns out – the Mongstad project will *not* be in the lower range of these costs. The next chapter provides background information about climate change, carbon capture and storage (CCS) and the Mongstad project.

How costly are these projects in general and this project in particular, assumed to be? What are the uncertainties related to these costs? What is the potential for CCS as a climate mitigation strategy? The third chapter is a discussion of the potential costs of this project. First, I will provide a bottom-up analysis of the costs of generating electricity from fossil fuels with and without CCS, and how various prices of carbon might affect the competitiveness of each technology. Then I compare different cost estimates of CCS from different sources. This is to get a rough understanding of the expected costs on CCS implemented on gas-fired power plants in general, although the costs are very uncertain and depends on project-specific factors.

Ironically, Statoil and the government have already been involved in a financial scandal at Mongstad. The upgrading of the refinery in 1987 resulted in a huge budget deficit: 6 billion NOK (or approximately 1 billion USD). The designation 'a mong' was used for years as a synonymous of the amount 6 billion NOK.

There are obvious uncertainties related to the costs of this large project. Statoil is familiar with the technology, and is therefore better informed than the government. This leads to asymmetry of information related to exogenous variables affecting the costs, like Statoil's technological possibilities or the difficulty in implementing certain productive tasks. The effort made by Statoil to minimize the costs can not be easily monitored by the government, and is an example of information asymmetry related to an endogenous variable. Because the government represents the public interest it has a special obligation to ensure that any agreement it enters into is in line with the public interest. It is in the public interest that all parties entering into a contracted agreement with the government have incentives to keep costs at a minimum. Statoil is concerned about their profits, and will not minimize the costs of the project or reveal their technological possibilities if that is not what maximize their profits.

Given that the government has decided to invest in this project – how should they proceed? How might this information asymmetry problem affect such a contract? And are these problems taken into account in the already existing contract? The forth chapter introduces the theory of incentives. I use this to again discuss why CCS, especially in a CO_2 value chain, is difficult to implement without governmental support. Finally, I discuss the characteristics the contract should have according to the theory of incentives, and further whether the actual contract embodies these characteristics. I will show that when such asymmetry exists, the government is forced to give up costly rents to Statoil, and to mitigate these costs, allocations are distorted away from first-best allocations. Finally, I will show that the actual contract is not optimal, even though it gives Statoil some incentives to minimize the costs.

2. Background

Here, I will first give some background information on climate change, Norway's commitment and the economical policy instruments in use. Then I introduce the Mongstad project, and explain what carbon capture and storage (CCS) is and why this will be implemented at Mongstad.

2.1 The economics and politics of climate change

The last year has been remarkable when it comes to climate policy. First, the International Panel of Climate Change (IPCC) published the Fourth Assessment Report[1] confirming that the climate change is man-made, that the effects might be catastrophic on eco-systems, societies and economies, and that drastic reductions in emissions must take place to avoid the worst effects. Emissions of greenhouse gases, such as carbon dioxide (CO_2)[2], contribute to global warming. Second, the Stern review[3] claimed that the mitigation costs that seem large today, are moderate compared to the costs of a 'wait-and-see' strategy.

Climate change is possibly the best, or most serious, example of one type of market failure: externalities. Individuals or firms do not suffer the full burden of producing CO_2, but the society does. Private costs can be equated to the social cost by implementing a cost of emitting CO_2 – either by quotas and a market for carbon, or by imposing a carbon tax. However, this is quite problematic. Climate change is a global problem – *affecting* all countries to some extent, and *affected by* all countries: it does not matter where the CO_2 is emitted, it will still have the same damaging impact. Ideally, all countries should cooperate and impose the same costs on pollution to avoid the problem of free-riding: a country would still benefit from the other countries emission reductions even if it is not participating and cutting its own emissions. Such cooperation turns out to be very difficult. Today, economic growth is closely connected to increased emissions because of increased demand for energy.

[1] IPCC (2007).

[2] There are several gases contributing to global warming. CO_2 represents the largest contribution because of the large quantities emitted.

[3] Stern (2006).

One step towards creating a global carbon price has been made. The Kyoto Protocol entered into force in 2005, signed by 166 countries. The developed countries have agreed to reduce their overall emissions of six greenhouse gases, included CO_2, by at least 5 % below 1990 levels over the first commitment period from 2008-2012. This way, a cap on emission has emerged. Countries are free to choose, within their national limits, how best to deliver emission reductions nationally. Flexible mechanisms are created that enable these countries to meet their commitments efficiently. International Emissions Trading (IET) allows trading of national quotas between countries. Within this framework, the European Union (EU) has developed its own Emission Trading Scheme (ETS). The first trading period from 2005-2007 was considered a trial period. The price has varied a lot – from nearly 0 to 30 €/ton CO_2. The second period is from 2008-2012. Emission reducing projects in other countries can also be used for countries to meet their Kyoto commitments. Joint Implementation (JI) is hosted by other developed countries, and the Clean Development Mechanism (CDM) by other developing countries.

In 2005, Norway developed its own trading scheme that included the industries which already paid taxes on their emissions. Already in 1991 Norway had introduced a CO_2 tax of approximately 300kr/tCO_2. From 2008-2012, the Norwegian system will be expanded, including some sectors that used to pay the CO_2 tax, and will become an integrated part of the EU ETS.

In theory, imposing a CO_2 tax or tradable quotas will have the same effect: emission reduction will be done in a cost effective way by equating the price of emissions among polluters. Now that an international quota market is established, there will be no need for a CO_2 tax, given that this system is efficient. There is also discussion on how the quotas should be distributed, whether they should be given away for free, sold or auctioned. In theory, these are equally good instruments if the number of quotas to be given away is fixed. Firms will have a direct cost from purchasing quotas in the marked if they are emitting more than the quotas they possess. Alternatively, they could sell quotas instead of emitting: this makes polluting equivalent to lost income from not being able to sell. The market will make the firms buy or sell quotas until the marginal cost of polluting is equalized among polluters, making the emission reductions cost effective. A potential problem with free quotas is new firms, and firms expanding their production. If they are given free quotas, the cost of polluting will not be properly taken into account in their investment decision.

2.2 The Mongstad project

In 2005 Statoil applied for a license to build a combined heat and power (CHP) plant without carbon capture at Mongstad. This type of plant is very efficient since it also exploits some of the heat needed to burn the natural gas when generating electricity. The planned installed capacity is 280 MW of electricity and 350 MW of thermal energy (heat). The already existing refinery at Mongstad would be supplied with heat and some of the electricity. Surplus electricity would be in part sold to the Troll A petroleum field, and part of it would be available for other uses. The estimated net increase of CO_2 emissions is 900,000 tons, and total emissions at Mongstad to be 2.7 million tons.

2.2.1 Carbon capture and storage (CCS)

However, producing electricity from gas-fired power plants can be done in a cleaner way. It is possible to capture the CO_2 by separating it from the gas. Then, after compressing it, the CO_2 can be transported to a suitable storage location, and injected. This way, the CO_2 will not be emitted into the atmosphere and therefore not contribute to global warming.

This can also be applied to coal-fired power plants and industry. The CO_2 content of the flue gas from gas-fired power plants is lower than that of coal, which makes it more expensive per unit to capture CO_2 from a gas-fired power plant.

There are several ways to **capture** CO_2, and these can be divided into three categories[4]. The most known and well-developed technology is *post-combustion*. The CO_2 is separated from part of the flue gases produced by the combustion of the natural gas. These systems normally use a liquid solvent to capture the CO_2 present in the flue gas stream.

Pre-combustion, as the name indicates, is a method that converts the gas into CO_2 and hydrogen before it is used to generate electricity. Hydrogen is a carbon-free energy carrier that can be combusted to generate power and/or heat. Although the initial steps of this method are more elaborate and costly, the higher concentrations of CO_2 in the gas stream and the higher pressure make the separation easier.

[4] IPCC (2006).

The last method, *oxyfuel combustion*, adds oxygen when burning the gas. This results in high CO_2 concentrations in the gas stream and, hence, in easier separation of CO_2 and in increased energy requirements in the separation of oxygen from air. These systems are being studied in gas turbine systems, but conceptual designs for such applications are still in the research phase.

Transportation of CO_2 can be done either by ships or pipelines, the latter preferred for transporting large amounts for distances up to around 1,000 km. This operates as a mature market technology, whereas shipping of CO_2 has only been carried out on a small scale.

The uncertainty related to CCS, apart from the uncertainties regarding the costs, is related to **storage**. There is limited knowledge about the different methods when it comes to leakage and environmental impact. Storage of CO_2 in deep, onshore or offshore geological formations uses many of the same technologies that have been developed by the oil and gas industry and has been proven to be economically feasible under specific conditions for oil and gas fields and saline formations, but not yet for storage in unminable coal beds. Ocean storage is another option. This could be done in two ways: by injecting and dissolving CO_2 into the water column (typically below 1,000 meters), or by depositing it onto the sea floor at depths below 3,000 meters where CO_2 is denser than water and is expected to form a 'lake' that would delay dissolution of CO_2 into the surrounding environment. This is still in the research stage. Further, it is possible to react CO_2 with metal oxides and produce stable carbonates, but this is energy intensive and still in the research stage. CO_2 for industrial uses is another opportunity, but this potential is small.

CO_2 used for Enhanced Oil Recovery (EOR) could lead to additional revenues from oil recovery. By injecting CO_2 into the reservoirs, more oil could be extracted. This could also be applied to gas- and coal production. This could be done in addition to CO_2 storage.

At Mongstad, post-combustion is the method of interest. This is a well known technology to Statoil. They have since 1996 separated about 1 million tonnes of CO_2 annually from the well stream from the Sleipner West field at the North Sea continental shelf by using amine absorption technology. The CO_2 has been injected into the Utsira deep saline aquifer formation to save the Norwegian tax on CO_2 emissions. Evidence from this project is that there is no leakage from the storage.

2.2.2 *Political difficulties*[5]

Gas-fired power plants have been a difficult topic for Norwegian politicians throughout the last decades. In 2000, this was the reason for the government resigning. The need for energy and electricity for households and industries on one hand, and environmental concerns on the other, makes it difficult. Cleaning gas-fired power plants by implementing CCS has been largely discussed the last years. Some politicians and environmentalists are still against it. They argue that resources should be allocated towards renewable resources, since CCS is only a temporary solution. Among some parties, both politicians, industries and environmentalists, however, clean gas plants has been a preferred solution, although they do not agree on who should bear the costs and risk.

International commitment makes it difficult to allow new large sources of CO_2 emissions. The Stoltenberg government declared in October 2005 that all licenses given to new gas plants should be based on CCS. Despite this, the Norwegian Water Resources and Energy Directorate (NVE) approved Statoil's application in the summer of 2006 without any cleaning requirements. This led to hard negotiations during the fall 2006. There were several possible outcomes.

The government could have let Statoil proceed with the project without CCS. This would have been in Statoil's interest, but this could not have been accepted by all the political parties in the government, and would therefore have led to a governmental crisis, and probably to the end of the governmental coalition.

The government might have been able to force Statoil to implement CCS. Statoil, however, had been signaling that this would be too expensive and lead to a cancellation of the entire project. This would not have been an acceptable outcome for the government either.

The government could help financing the capture facility, as they ended up doing. This pleased environmentalists and liberal politicians, but not economists and others who are skeptical to the use of public resources in a non-optimal way[6]. Moreover, it could be

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[5] Tjernshaugen (2007).

[6] Strict economical calculations show that as a mitigation option, investing in Mongstad is by far one of the most expensive ones. See further discussion in chapter 3.

difficult because of competition regulations[7]. However, this was the only feasible outcome for the government.

2.2.3 The contract[8]

In 2006, the Norwegian government undertook an agreement with Statoil to establish the world's largest full-scale CCS project in conjunction with the projected combined heat and power plant at Mongstad.

The power plant will start producing in 2010. Implementing CCS will be done in two steps:

Step 1: Development of technology. The two parties will establish a technology company/-partnership that will build a first capture facility with capacity to capture at least 100,000 ton CO_2 per year. The purpose is to identify, develop, test and qualify possible technological solutions, and hereby reduce the costs and risks related to building and operating full-scale capture facilities. Statoil is committed to own 20% of the technology company, whereas the government will own the remaining 80%. Other companies are invited to enter the project by taking over parts of the governments shares.

Step 2: Full-scale carbon capture of CO_2. From 2014, the combined heat and power plant at Mongstad will be operated with carbon capture. The planning of this will be done in parallel with step 1. The details regarding the investment decisions, including choice of technology and estimated costs, will be ready by 2012. At this time, the building of the capture facility at the power plant will get started. The parties have agreed upon choosing an accomplishment strategy that minimizes risk, and that building the future capture facility should not deteriorate the refinery's international competitiveness.
The Norwegian government will cover the investment- and operation costs of the Step 2 capture facility and also the costs of transport and storage. Any positive value of the CO_2 in a possible CO_2 value chain are going to be withdrawn the costs of the government.
Statoil are going to cover the costs equivalent of their alternative CO_2 cost if they had not implemented CCS (CO_2 costs corresponding to other Norwegian industry in competition

[7] The EU Commission is working on changing the rules regarding economic competition to make an exception for governmental support for CCS. See Bellona (2007): http://www.bellona.org/articles/EU_Commission_for_CCS

[8] Ministry of Oil and Energy (2006): "Samarbeid om håndtering av CO_2 på Mongstad – gjennomføringsavtalen"

with foreign industry). They are also obliged to cover 100% of any costs exceeding the estimated investment costs.

Nonetheless, increased costs due to exogenous factors, such as increased gas prices, will be covered by the government.

3. Costs

The aim of this chapter is first to give an understanding of the potential costs of CCS as a mitigation strategy in general. I show how the profitability of CCS on both coal- and gas-fired power plants depends on how strict current and future climate policies are. These are simple calculations based on one set of cost estimates. The second part discusses different cost estimates available for new gas-fired power plants only; this to give a picture on what in theory can be the expected cost for the Mongstad project. The last part compares these costs to Statoil's projected costs, and discusses why they differ. When the government enters into an agreement with Statoil, this is the information about the potential costs of the project that is known to both parties.

3.1 The effect of a carbon price on marginal costs

This is a bottom-up analysis of the costs of producing electricity from fossil fuels, where one coal-fired and one gas-fired technology are considered. I look at how a price on carbon may affect the competitiveness of coal and gas, on existing and new plants, and with and without carbon capture and storage.

3.1.1 The marginal costs of producing electricity

The supply of electricity depends on each plant's marginal cost of producing one unit more. An existing plant is willing to produce if their short run marginal costs, or their variable costs, are lower than the price they will get on the market. This is an *ex post* marginal cost: the cost of building the plant is considered a sunk cost, and do not enter the decision on whether to produce or not. The variable costs consist of two main categories: fuel costs and variable operation and maintenance (O&M) costs. These can be considered as labour and other inputs that vary with the production.

For renewables such as wind and solar, the only variable cost is the variable operation and maintenance costs, which are low. For fossil fuels, the fuel cost will be the largest component.

However, before a plant is built, the investment cost has to be taken into account. In bottom-up models, this is done by assuming a discount rate and an economic lifetime of the plant, as well as how much the plant will produce during a year, and this way find a cost of capital per kWh. In addition, there are fixed O&M costs which depend only on the plant size, and not on production.

This way, we get an *ex ante* marginal cost of producing electricity that will consist of three main components: capital costs, fuel costs and O&M costs[9]. These will be taken into account when deciding whether to build a new plant or not, and what kind of plant to build.
Burning fossil fuels leads to great emissions of the climate gas carbon dioxide, CO_2. Coal emits more CO_2 per unit of energy, 25.8tC/TJ, compared to natural gas, which emits 15.3tC/TJ[10]. Emissions per kWh will also depend on how efficient the plant uses the fuel. Coal-fired plants have a thermal efficiency of 35-50%, which is less than the 45-60% of gas-fired plants. These two factors both contribute to coal-fired plants being more polluting than gas-fired ones.

A price on CO_2 emissions will enter the marginal cost of producing electricity. Both the ex post and ex ante costs will get an additional component, the CO_2 cost.

3.1.2 Carbon capture and storage (CCS) - the effect on marginal costs

CCS can be applied to both existing and new fossil fuel plants. It will cost more in terms of kWh to retrofit an existing plant than to integrate it when building a new plant. Because coal contains more carbon than natural gas, capturing carbon from a coal plant is cheaper than from a gas plant per unit. In addition to this capture cost, there will be a transportation cost and a storage cost. The transportation cost is highly depending on the location of the plant and already existing infrastructure. Implementing carbon capture will reduce the CO_2 emissions with approximately 80%, and will therefore considerable reduce the CO_2 cost.

In Norway, several individual projects, included Mongstad, have concluded that CO_2 for enhanced oil recovery (EOR) is not profitable[11]. The Norwegian Petroleum Directorate also concluded in a study that CCS for EOR is not yet profitable. Bellona, on the other hand,

[9] Both fixed and variable O&M costs.

[10] Reinaud (2003).

[11] See for example http://www.adressa.no/nyheter/okonomi/article887582.ece

claims that this is profitable if several projects are coordinated and proper infrastructure is developed, see Bellona (2005). I choose not to include possible revenues from EOR here in my analysis.

The costs of implementing CCS at Mongstad can most likely be compared to retrofitting existing gas-fired power plants.
Studies[12] estimate that examples of the total additional cost per kWh can be

- 3,60 €cents/kWh for existing coal-fired plants (EC)
- 1,39 €cents/kWh for new coal-fired plants (NC)
- 4,05 €cents/kWh[13] for existing gas-fired plants (EG)
- 1,54 €cents/kWh for new gas-fired plants (NG)

The reduction in the CO_2 cost, which will determine if it is profitable or not to implement CCS, will be highly dependent on the CO_2 price.

3.1.3 The merit order at various CO_2 prices

The merit order of the market is a ranking of generators, from those with the lowest average variable costs to those with the highest. If all existing technologies on the market were included, adjusted by their market share, this would represent the supply curve of electricity. Here, I have just included the fossil-fuel technologies that I have studied, both existing and new, to illustrate the differences in marginal costs. The results are presented in figure 3.1. I consider four possible carbon prices: 0, 20, 50 and 100 €/t CO_2[14]. Colours are used to illustrate the degrees of emissions, with the darkest one marking the largest emissions, coming from existing coal plants. The power plants with CCS are white. Abbreviations are explained in the bow below.

<u>Abbreviations used for the different technologies in figure 3.1</u>

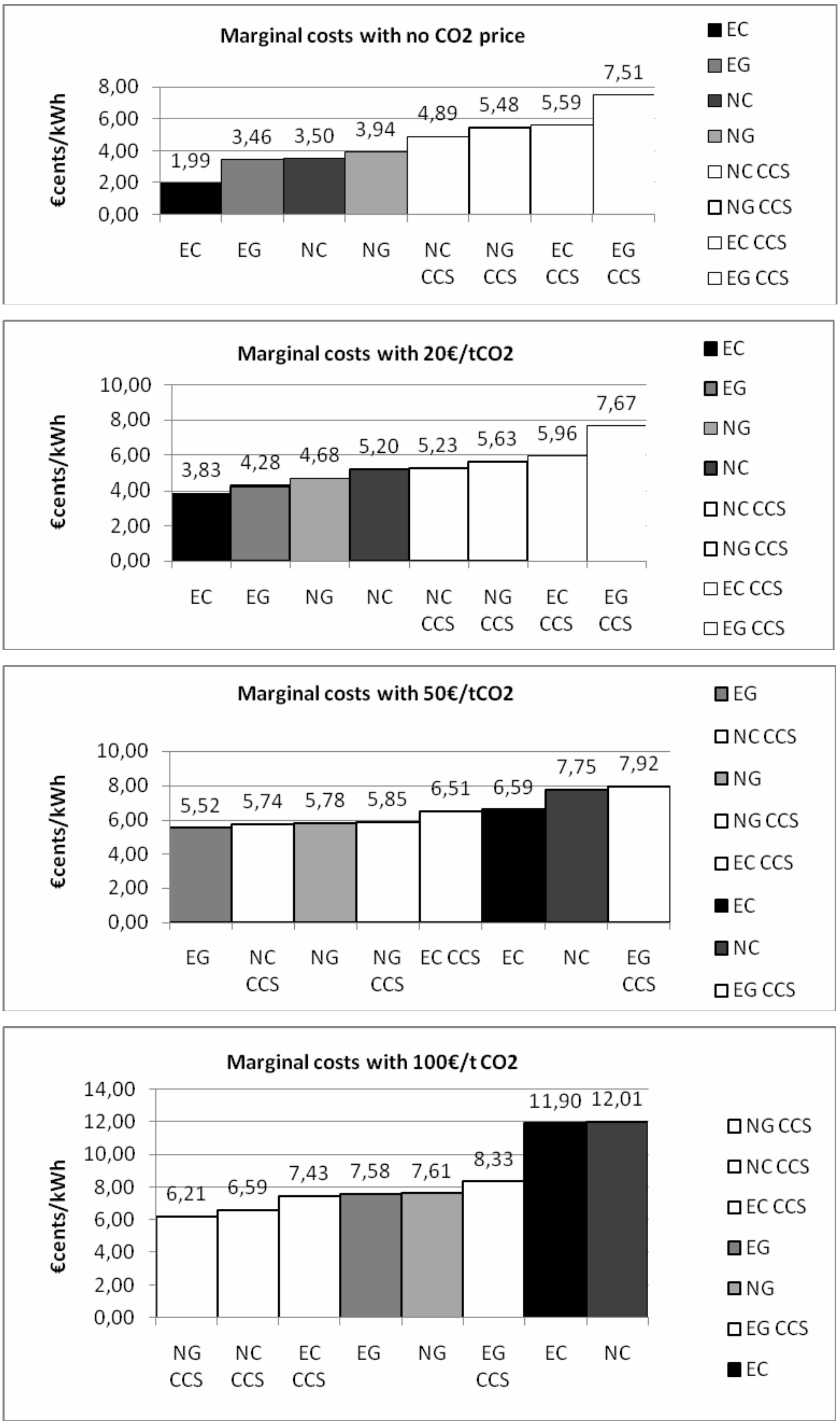
EC	*Existing coal-fired plant*
EG	*Existing gas-fired plant*
NC	*New coal-fired plant*
NG	*New gas-fired plant*
EC CCS	*Existing coal-fired plant with CCS*
EG CCS	*Existing gas-fired plant with CCS*
NC CCS	*New coal-fired plant with CCS*
NG CCS	*New gas-fired with CCS*

[12] IPCC (2005). See appendix for explanation.

[13] Own assumption: see explanation given in 'Appendix 1: Assumptions and calculations'

[14] Both the Stern (2007) and IPCC (2006) give explanations on what carbon price is needed to reach various stabilization levels of CO_2, and these prices are consistent with theirs.

Figure 3.1: *Change in the merit order at different CO_2 prices.*



Explanations of the results in figure 3.1:

No CO_2 price – baseline case: Typically, an already built coal plant will be operated at base load[15] as its marginal costs are low compared to those of a gas plant, and it takes less time to restart. The price of natural gas has been higher than that of coal[16], and since the largest cost component is fuel, the coal plant is cheaper. Building a new coal plant is more expensive than a new gas plant, and a new gas plant is more efficient than a new coal plant. With no CO_2-price, a plant with CCS will not have the advantage of a lower CO_2 cost. The only difference in their marginal costs is the additional cost of CCS. This makes all CCS plants more expensive than regular plants. We also see that new CCS plants are cheaper than the retrofitted existing plants.

CO_2-price = 20€/tCO_2: The price of a new coal plant has increased from 3.5 to 5.2, and has become more expensive than a new gas plant, which has a marginal cost of 4.68. This is the only change in the merit order at this price. Retrofitting existing plants are still the most expensive, since the saved CO_2 costs are still relatively low.

CO_2-price = 50€/tCO_2: At this carbon price, things start to happen. The marginal costs are more evened out, ranging between 5.5 and 8, and the plants with CCS are getting competitive. The retrofitted gas-fired plant still has the highest marginal costs, but is closely followed by new and existing coal plants without CCS: at this price, coal plants with CCS will be cheaper than those without.

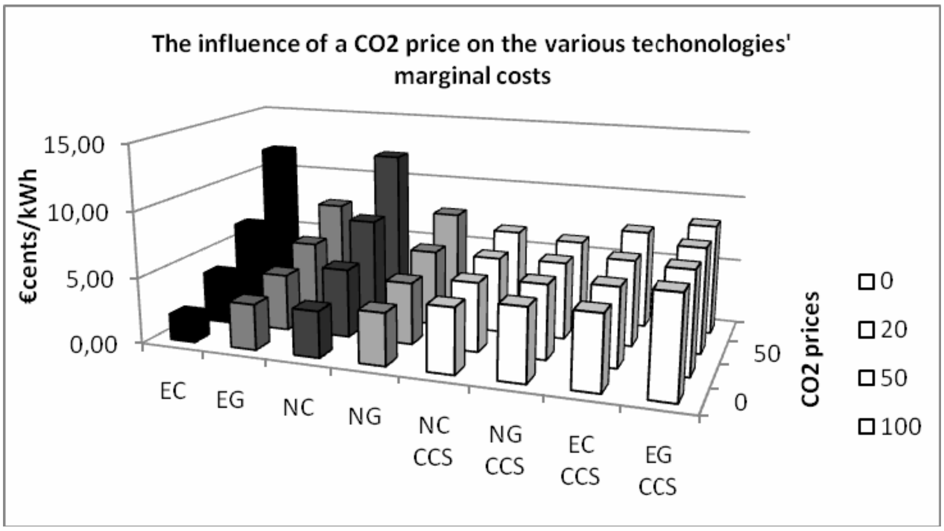
CO_2-price = 100€/tCO_2: At this price, both existing and new coal without CCS are clearly worse off than the others. The winners are new plants with CCS, followed by gas-fired plants, both new and existing. Here, it is also cheaper to build a new gas-fired power plant with CCS than without. Note that even at this price it is not profitable to retrofit an existing gas-fired plant. The marginal cost of existing coal, which is the cheapest in the baseline case, is now 500% higher. Existing coal, with a marginal cost of 11.90 €cents, is 4.47 €cents more expensive than a retrofitted coal plant. This also happens for new coal plants, with a

[15] A base load power plant is one that provides a steady flow of power regardless of total power demand. (Wikipedia)

[16] IEA, 2006.

marginal cost of 12.01 €cents/kWh that is 5.42 €cents/kWh higher than for a new coal-fired plant built with CCS.

Figure 3.2: *CO_2 price: the influence on the marginal costs***.**



At what carbon price will it be profitable to implement CCS? Figure 3.2. illustrates that CCS plants are less affected by an increased CO_2 price, and will be able to compete with regular plants if the carbon price gets high enough. For both of the coal-fired plants, this happens at somewhere between 20 and 50 €/tCO_2. For a new gas plants, this happens at a price between 50 and 100 €/tCO_2. For existing gas plants, however, this does not even happen at a carbon price of 100 €/tCO_2. The costs of implementing CCS at the power plant at Mongstad are probably most comparable to the costs of an existing gas-fired power plant, as the power plant was projected without CCS. This will be discussed further in chapter 3.2.2. From this analysis, we see that implementing CCS at Mongstad will only be profitable if the quota price increases substantially.

3.1.4 Discussion

These results are quite interesting, but such a simple analysis has some important limitations for predicting future production costs.

There is a lot of **uncertainty** when it comes to CCS. It is a new and unproved technology, at least when it comes to larger full-scale projects. This might lead firms to need significant differences in expected costs to be willing to choose CCS.

The **fuel prices** are assumed to be constant. This will be an endogenous variable depending on how much electricity that will come from gas fired plants in the future. Natural gas is also an exhaustible resource. For a given stock, the price will increase as the resource becomes scarcer. Predictions[17] indicate that the price of both coal and natural gas will increase in the future.

The **access** to coal and natural gas will also affect the investment decisions. Natural gas is costly to transport, and is often dependent on infrastructure. Building power plants close to the natural gas source could solve this problem. The supply security is also important. Relying on imports from other countries, like Russia, is a situation many countries would like to avoid.

Another thing worth mentioning is **renewables**. There are other ways to reduce emissions from electricity generation besides CCS, and it is likely that some of these will be competitive at approximately the same CO_2 price as CCS. However, the costs of the various renewables are highly site dependent, and will vary from country to country. Technological progress and cost reductions are dependent on amount invested in each technology, and it is common belief that it will take time before renewables can fully compete with fossil fuels. It will also take huge investments in renewables to be able to replace it – the size of a fossil fuel plant is typically 500-1000 MW, compared to 1-150 MW for renewables. This is why CCS is considered to play an important role in emission reductions.

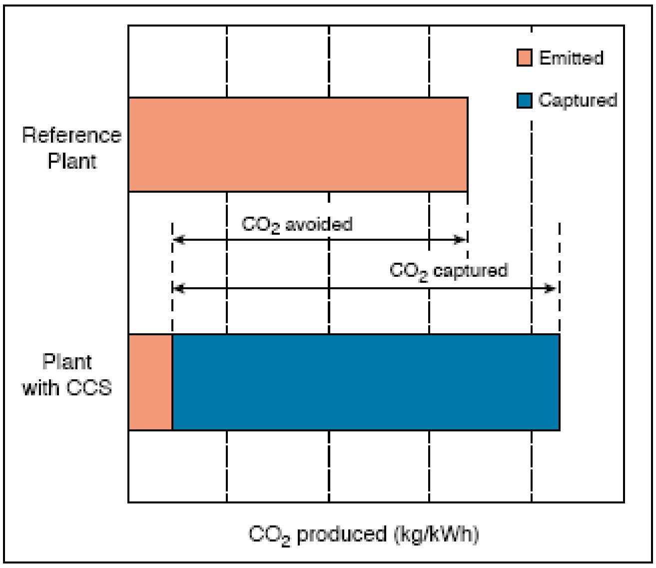
3.2 Carbon Capture and Storage Cost Estimates

There are several ways to express the increased costs of CCS. The two most important changes will be the increased investment costs from building the capture facility, and the decrease in efficiency, which leads to increased fuel costs.

One way is to look at the increased marginal costs of electricity production, as I did in the previous chapter. These will depend on assumptions, the most crucial one being the price of natural gas. This price has increased the last years, and this might change the forecasts. The gas price is difficult to forecast since it depends on many variables, both technical (the total gas reserves, the extracted amount), economical (demand, market concentration and market power) and political (uncertainty regarding supply).

[17] IEA (2005).

Figure 3.3: *Illustration of the difference between CO_2 captured and CO_2 avoided.*



Another option is to consider the mitigation costs. Based on the same assumptions, it is possible to find a price of CO_2 avoided – this means dividing the costs on the amount of CO_2 you get rid of by implementing CCS. This can be compared to the CO_2 price directly; if it is lower than this, there will be an expected gain from implementing CCS. If not, it will be cheaper to emit all of the CO_2 from the plant, and pay the CO_2 price. Figure 3.3 shows the difference between CO_2 captured and CO_2 avoided: as the efficiency is decreased when implementing carbon capture, more fuel is used, and more CO_2 produced, therefore the amount of CO_2 captured is larger.

Alternatively, one can consider the investment costs and annual operation costs of CCS. The investment costs will not depend on assumptions about gas prices, but the annual operation costs will.

3.2.1 Cost estimates for CCS on gas-fired in general

IPCC's *Special Report on Carbon dioxide Capture and Storage* offers seven recent case studies[18]. The investment costs are 700-970 EUR/kW, and this is 64-100% more than the reference plants. The increases of marginal costs range from 37-85 % over reference plant. The cost of CO_2 avoided ranges from **29-70 EUR/tCO_2**. This includes transportation costs of 0-3.8 EUR/tCO_2 and geological storage costs of 0.5-6.4 EUR/tCO_2. The results are based on natural gas prices of 2.2-3.4 EUR /GJ.

[18] Currency conversion: 1 EUR = 1,3 USD

The International Energy Agency's (IEA) *Prospects for CO_2 Capture and Storage* offers several examples of technologies – one with chemical absorption. The increased marginal costs are 40.8 %, and the cost of CO_2 avoided is 27.5. This is without transportation and storage. Assumed gas price is 2.3 EUR /GJ. The estimated transportation costs are 1.5-15.4 EUR/tCO_2 (depends on scale and distance). 1.5-38.5 EUR /tCO_2 injection costs (low end refers to aquifers – say 1.5-3.9). This gives a possible range of **26.9-46.2 EUR/tCO_2** in total.

The World Energy Council's (WEC) study from 2000, *World Energy Assessment: Energy and the Challenge of Sustainability*, also provides cost estimates for CCS. Investment costs are 698 and 706 EUR/kW; this is an increase of 100 and 120 %. The marginal costs increase with 54 and 62 %. The costs of CO_2 avoided are **45 EUR/tCO_2** and **49 EUR/tCO_2**. Gas price assumption is 2.36 EUR /GJ.

Other studies[19] are Anderson and Newell (2003): **40 - 59 EUR/tCO_2** and Hendriks et al. (2000): **42 - 85 EUR/tCO_2**.

3.2.2 How costly is the Mongstad project assumed to be?

'Bakgrunn for vedtak', the Norwegian Water Resources and Energy Directorate's (NVE) report that justifies their decision to say yes to an allowance for Statoil's combined heat and power plant, reproduces Statoil's cost estimates. The costs of CCS are assumed to be 450-660 NOK/tCO_2 (or equivalently **56-83 EUR[20]/tCO_2**). The investment costs are 6 billion NOK, and the annual operation costs are assumed to be in the range of 340-550 million NOK/year.

In the Ministry of Oil and Energy's (MOE) presentation of the Mongstad project, Statoil's estimates are also given. Statoil claims that the capture facility could cost approximately 3-4 billion NOK. In addition, there will be costs of transportation and storage, adding another 1-2 billion NOK. This gives a mitigation cost of at least 500 NOK/tCO_2 (**63 EUR/tCO_2**).

The Norwegian Petroleum Directorate (NPD) has published a report on the possibilities of using CO_2 for enhanced oil recovery (EOR) on the Norwegian continental shelf where they give an estimate on the costs of CCS on a gas-fired plant in Norway. They are costs assumed

[19] As used in Torvanger (2005).

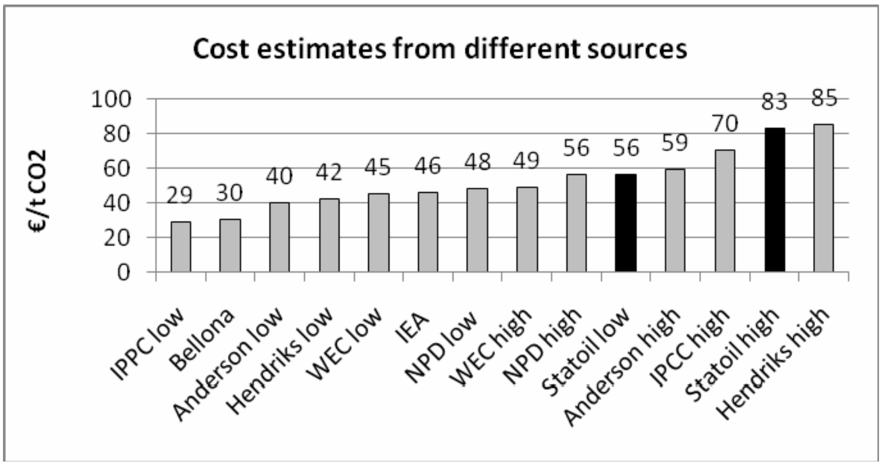
[20] Currency conversion 1 EUR = 8 NOK.

for Mongstad or Kårstø. Here the investment costs are 7.5 billion NOK, and the annual operation costs are assumed to be 5.2 billion NOK (over ten years, giving 520 million NOK/year). This gives costs of 383 – 448 NOK/t CO_2 (**48 - 56 EUR/tCO_2**).

This report has been criticized by Bellona (2005): 'The NPD report bases its conclusions on numbers from 2000 and 2002, which are twice as expensive as the Carbon Capture Project (CCP) and Aker/Kværner assessments.' They further state that 'Before Christmas 2004, Aker/Kværner/GassTek published a study indicating that the cost for a capture facility that could be readily built by 2007 would be below NOK 200 (EUR 25) per tonne CO_2.'

3.2.3 The projected costs of the Mongstad project compared to other studies

Figure 3.4: *An illustration of Statoil's projected costs of the Mongstad project compared to other studies.*



As illustrated in figure 3.4, the cost estimates of Statoil are high compared to other studies. At first sight, it might seem like Statoil is exaggerating the costs to avoid that the government forces them to implement CCS with no financial support. However, a possible explanation is that the plant was initially projected as a plant without CCS. This makes the costs similar to retrofitting an existing plant. Choosing other types of equipment, like turbines, and another design in general would have made it less costly to implement CCS. NVE decided not to make Statoil re-project the plant, as this would take several years and cost several million NOK[21]. Another factor that might explain the differences is the gas price assumptions – Statoil might have used a higher price in their calculations.

[21] NVE (2005).

4. Theory of incentives

First, I will use the theory of incentives to explain why the firms themselves might fail to bring carbon capture and storage to the market. Then I introduce two types of information asymmetry, moral hazard and adverse selection, and explain why this is relevant to the Mongstad project. The existence of such asymmetry will affect the optimal contract, and I use a model to show this. Finally, I compare this to the actual contract.

4.1 Some possible explanations on why the market might fail to develop CCS

A large project like carbon capture and storage will require new infrastructure and large investments. In addition, as shown in chapter 3, the costs are still high and the profitability of CCS is uncertain. At least if the CO_2 is to be used for enhanced oil recovery (EOR), power plants and oil fields must coordinate their decisions, and this might lead to problems. First, I will introduce the hold-up problem, and discuss how it might be relevant to CCS. Then I will discuss why the steep learning curve and economics of scale characterizing CCS might make firms reluctant to be the first to invest, and that this leads to a too slow, or non existing development of such projects.

4.1.1 The hold-up problem

When two firms are about to get involved in a possible project, they might have to make project specific investments. If they can commit to a binding contract up-front, the trade can be carried out efficiently. However, if it is not possible, for various reasons, to make such a contract, potential problems arise.

Consider the case where in period 0, the two firms make a contract. One of the firms makes a relationship specific investment in period 1. In period 2, when trade is to take place, the other firm will have a stronger position – if the contract is not binding, it can extract all or most of the gains from trade. Being foresighted, the first firm will be less willing to make the investment, or not willing at all, and the project will not be realised. This is known as the hold-up problem – the mutual dependence keeps profitable projects from being realised.

4.1.2 *A CO_2 value chain as a potential hold-up problem*[22]

Carbon capture and storage is a mitigation strategy that stops CO_2 from being emitted into the atmosphere. But in addition to having a value when being stored that corresponds to the carbon price, there might be a market for the gas itself. Oil producers can inject CO_2 in their oil fields, leading to more oil being extracted from each field. This is known as enhanced oil recovery (EOR). CO_2 has the quality of making the oil thinner, and thus easier to extract. This will naturally provide extra revenue for the oil producers, and accordingly, they will have a willingness to pay for this CO_2. Today, natural gas is used for the same purpose. This has an opportunity cost since the natural gas otherwise could have been sold at the market.

However, to be able to use CO_2 instead of natural gas or water, some irreversible investments must be undertaken to prepare the oil fields to start this last production phase. To be willing to make these investments, the oil producers must be sure that they will get CO_2 delivered – if not, their investments will not give them any revenue. The suppliers of CO_2 could exploit this, demanding a higher price, since the use of CO_2 is the only way to produce more oil from the field after the investments are made. Foreseeing this, the oil fields might not want to make these investments.

Each field will only need the gas at a certain period of its lifetime. This period is not always easy to foresee, which makes the demand for CO_2 very uncertain. To mend this problem, CO_2 could be temporary stored, and delivered when it is needed. In addition, this short period of demand makes the CO_2 suppliers need several oil fields as buyers, which requires several oil fields to undertake these irreversible investments. Several buyers also imply that the price will be more uncertain, as it depends on aggregate demand. Another investment needed, is pipelines for transportation. This will require large initial investments, but small variable costs. The alternative, transportation by ships, do not require large investments, but the variable costs are large.

For CO_2 to be used for EOR, large amounts of it are needed. Because of this, pipelines seem to be the best alternative. Another consequence of this is that several suppliers of CO_2 are needed. The Norwegian Petroleum Directorate (NPD) showed that there was a willingness to pay for CO_2, but only in large amounts – larger than what Mongstad alone could provide.

[22] Hustad, C.-W. et al. (2004)

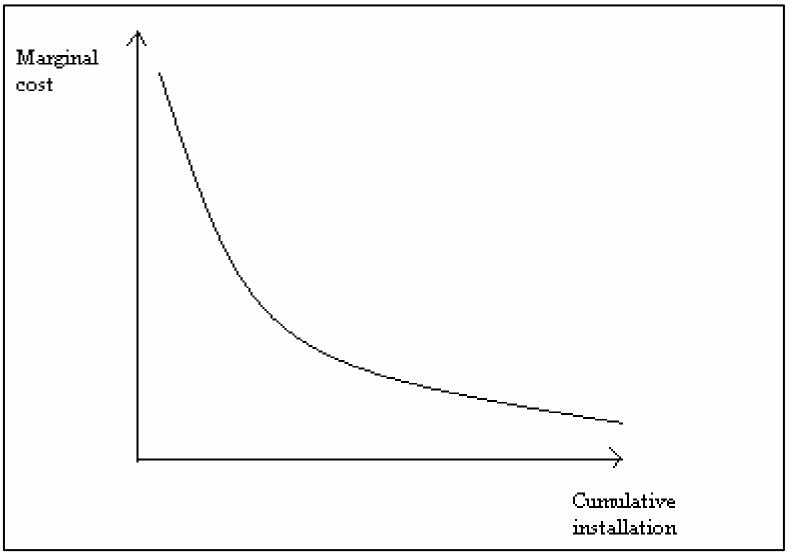
This complicates the issue further – coordination between firms in such an uncertain project will probably prove difficult. Firms of different sizes and locations might have to cooperate on infrastructure to be able to get the CO_2 both to and from the temporary storage location.

If a power plant has already implemented CCS, the oil fields might be able to get the CO_2 at a low price, since they represent the only market for CO_2. Any positive net price will be better for the power plant, since the alternative 'price' they get from storing it is zero. As the power plants know this up front, they would not have incentives to invest in CCS if the profitability of the project was highly depending on expected revenue from selling the CO_2 to oil fields. The problems with making a binding contract on beforehand could come from the oil fields not being able to commit to buying. Exogenous factors like the oil price, that is difficult to predict, will influence the decision on whether to continue producing or not, and hence, whether to demand CO_2 or not.

4.1.3 Learning curve and economies of scale

Historical experience shows that costs tend to decline with investment and operating experience. When data on marginal costs are plotted against cumulative installation, a downward sloping trend often appears. A curve can be drawn to fit this trend, and this is called a learning curve. With technologies and projects with steep learning curves, firms would rather see other firms undertake the first, costly investments. If there is diffusion of know-how, the fruits of this investment will not only come in the hands of the investing firm, but on the others' as well. This way, firms will choose a 'wait-and-see' strategy.

Figure 4.1: *Illustrative learning curve for a new technology*



This is relevant to both the Mongstad project itself and the potential CO_2 value chain. The learning curve for capture facilities is assumed to be steep, as well as the experience made from a large scale storage and EOR.

When it comes to a project,

firms might want to come in at a later stage, after the first firms have invested. They will be able to do this, as the investments are already made, and due to economies of scale, the variable costs might come down as more firms join. This is known problems before the projects are started, and again, this can lead to projects being abandoned.

For the CO_2 value chain, this could be a problem. This is a very risky project, and as I explained above, it is crucial for the profitability that several firms join. Adding more buyers and sellers will make the infrastructure less costly, in terms of traded units.

4.1.4 Possible solutions

It is quite clear that there is a potential role for the government as a coordinator. But even though this could reduce the problems discussed above, the government should consider the enormous uncertainties in this large project. As discussed in the previous chapters, CCS might play an important role in reducing the climate problem, but it is not evident that Norway should undertake such large investments.

It is also argued that if a project is profitable enough, the market will find a way to cooperate and form binding contracts themselves. As for the CO_2 value chain in Norway, it might be profitable[23], but it will depend on many independent actors and variables like the oil price, that is very difficult to forecast. Most costs of the project will come in a few years, whereas the revenues will come much later on.

Joint ownership is another solution. This is partly realised when it comes to this particular case, as for example Statoil is the owner of both power plants selling and oil fields buying CO_2. But still, several actors are needed in this value chain.

The governmental intervention at Mongstad will help Statoil to bear the burden of being the first firm to invest in full scale carbon capture. Important experience might reduce the uncertainties of such projects, and make the next projects less costly.

[23] Bellona (2005) has the most optimistic calculations, claiming that CCS for EOR will give substantial revenues, given that the government undertakes heavy investments.

4.2 Contract theory

In the last chapter, a contract seemed to solve the problem with implementing carbon capture and storage. Here, I will first discuss theoretical problems that might appear with such a contract. Then I will discuss how this applies to this case in particular, recalling the discussion from last chapter. Finally, I will look at the existing contract, and if these problems seems to have been taken into account.

4.2.1 Adverse selection and moral hazard

A regulator, like the Norwegian government, wants a firm like Statoil to realize a project. All economic agents, be it the government or a firm like Statoil, have a utility function or profit function that they want to maximize. Most often the firm has a proper utility function to maximize that does not coincide with the one of the regulator. Therefore, an enforceable contract that controls that the choices made in the production would be in the regulator's interest must be made. The problem arises when the firm has private information – it knows more than the regulator about the costs of the project. This information can be of two types. The firm might have private knowledge about its costs or valuation that is ignored by the regulator; this is known as *adverse selection*. The exact opportunity cost of this task or the precise technology used are examples of such private knowledge. In general, this allows the firm to extract a rent from its interaction with the regulator even if its bargaining power is poor. The other version involves an action that the firm might take, or not take, that is unobserved by the regulator; this is known as *moral hazard*. These actions might affect the value of trade or the firm's performance. A leading example is effort, which positively influences the firm's production costs but also create a disutility for the firm. To be able to get the firm to make the wanted level effort, the transfer to the agent should be depending on the result, leading the firm to make the effort to maximize his own gain from the interaction.

4.2.2 The Mongstad case – an optimal contract

Here, I will use a simple model[24] where a regulator wants to realize a single, fixed-size project, that has the value *S* for consumers, and a single firm has the adequate technology. I will assume that getting Statoil to implement CCS is the government's objective. In addition, they would like this to be done in the least costly way, both by giving Statoil incentives to

[24] Laffont, J.J. and Tirole, J. (1993). The model is taken from Chapter 1 'Cost-Reimburdement Rules', p. 55 - 62.

make an effort to minimize the costs, and by extracting Statoil's potential rents from the project.

4.2.2.1. General assumptions

Assumption 1: The regulator is subject to adverse selection and moral hazard.

Statoil has private information about its technology at the date of contracting, and its cost-reducing effort is unobservable by the government.

$$C = C(\beta, e, \ldots) + \varepsilon$$

where β is a technological parameter; a high β indicates an inefficient technology, hence C'_{β}, and e is the effort. Effort is assumed to reduce costs at a decreasing rate: C_e' and C_e''. The noise term, ε, stands for either forecast errors or accounting inaccuracies. C_{β}'. This analysis assumes that Statoil *has* a technology that will be used in the project. In reality, Statoil and the government are to agree on an appropriate technology after the contract is signed, and before the building of the capture facility starts. Statoil can use a technology they are familiar with from their other carbon capture projects, or get another firm to deliver the capture facility. However, the difficulty and costs of implementing any CCS technology on the power plant at Mongstad will be a parameter known to Statoil, but not to the government. Information on projected costs of the different technologies, as I provided in chapter 3.2.1., is known to the government. Hence, this assumption can be applied to the Mongstad case. In addition, chapter 3.2.1. showed that the costs of implementing CCS are very uncertain. This does not represent a problem as β can be thought of as representing an interval of costs, or that the cost function includes another uncertain variable, here represented by ε. This uncertainty is the same for both the government and Statoil; they have the same information about it. Hence, this uncertainty does not affect the results of this analysis.

Assumption 2: The realized cost, C, are observable. However, the government can not disentangle the various components of cost.

Assumption 3: Statoil can refuse to produce if the regulatory contract does not guarantee it a minimum level of expected utility.

This forces the government to respect a *participation constraint*. I let U denote the Statoil's expected utility. To make Statoil accept the contract, they must be made at least as better off than when choosing to abandon the project. This constraint becomes

$U \geq 0$.

Assumption 4: The regulator can operate money transfers to the firm.

In this case, this means that the competition restrictions from having an agreement with the European Union do not keep the Norwegian government from financing parts of this project.

Assumption 5: Statoil and the government are risk neutral with respect to income.

Statoil is a large firm involved in many projects. They might be risk averse when it comes to their total revenue, but risk neutral in each project as their risk is minimised through the involvement in many, different projects. The government is likely to be risk neutral.

Assumption 7: The firm cares about income and effort only.

The utility function can be written like this

$$U = t - \psi(e).$$

where t is the transfer received from the government, and $\psi(e)$ denotes the disutility of effort. Effort is costly, $\psi'(e)$, and the cost of effort is convex; $\psi''(e)$. For technical reasons: $\psi''' \geq 0$. Statoil's objectives would be to minimize their costs, but also obtain experience and know-how. This last objective will not be inconsistent with this simple utility function, as this will be fulfilled in any case by this project, independent of the contract's structure.

Assumption 8: The regulator faces a shadow cost of public funds $\lambda > 0$. This is because the money spent by the government is raised through distortionary taxes.

Assumption 9: The regulator's objective is to maximize total surplus in society.

This is a 'benevolent regulator assumption' that unlike my discussion about the political difficulties in chapter 2 neglects the fact that politicians might have other objectives, like maximizing the likelihood for being re-elected. Another thing the government has claimed is that they want the technology and the experience obtained to help reducing the future costs and uncertainties of CCS, to make it easier for others to implement as a mitigation strategy. I will not try to include this in the utility function: I will assume that the realization itself of this project will help promoting this.

Assumption 10: The regulator designs the regulatory contract.

4.2.2.2. Incentive schemes

A typical procurement contract has the government reimburse a fraction b ($0 \leq b \leq 1$) of the firm's monetary expenditure C. The government has two goals: promote cost reduction and extract the firm's rent. The government pays the firm's cost and then pays a net transfer to the firm:

$t = a - bC$

where a is a 'fixed fee' and b is the fraction of the costs born by the firm, and thus the power of the incentive scheme.

There are two common polar cases of such linear schemes:

1. The *cost-plus contract* ($b = 0$). The firm does not bear any of its costs. The cost-plus contract is an extremely low-powered incentive scheme. At the same time, the government is extracting all of the firm's rent, and will benefit from all exogenous factors reducing the costs.
2. The *fixed price contract* ($b = 1$). The firm is residual claimant for its cost savings. The government does not reimburse any of the costs; it pays only a fixed fee. The fixed-price contract is an extremely high-powered incentive scheme. However, the government will not be able to extract any rent from the firm.

In between the two extremes, we have *incentive contracts* with b strictly between 0 and 1. Real-world contracts are often linear, but some have nonlinear features such as a ceiling on transfers from the government.

If the government and Statoil have the same knowledge about Statoil's technology parameter (moral hazard but no adverse selection), the optimal regulatory contract is a fixed-price contract. The fixed fee is optimally set at the lowest level consistent with Statoil's participation provided that they choose the cost-minimizing effort, that is, the effort that minimizes $C + \psi(e)$.

When Statoil has private information about the technology parameter as well, optimal contracts are incentive contracts trading off effort inducement, which calls for a fixed-price contract, and rent extraction, which calls for a cost-plus contract. It can be shown that it is optimal for the government to offer a menu of incentive contracts. If a firm could be either efficient or inefficient, the inefficient firm should not be given the same contract as an efficient firm.

4.2.2.3. The model

The variables:

C	the cost of the CCS project
β	the efficiency parameter
e	Statoil's effort
U	Statoil's utility function
$\psi(e)$	Statoil's disutility from exerting effort with $\psi' > 0$ and $\psi'' > 0$ for $e > 0$
t	transfer from the government to Statoil
λ	shadow cost of public funds
S	value of the CCS project for consumers

The cost function of the CCS project is assumed to be

(1) $C = \beta - e$

Statoil's utility level can be written as

(2) $U = t - \psi(e)$

which implies this participation constraint

(3) $t - \psi(e) \geq 0$.

The net surplus of consumers/taxpayers is

(4) $S - (1 + \lambda)(t + \beta - e)$,

leaving the government with an ex post social welfare

(5) $S - (1 + \lambda)(t + \beta +-e) + t - \psi(e)$.

Adding and subtracting $(1 + \lambda)\psi(e)$, this can be rewritten as

(5) $S - (1 + \lambda)[\beta - e - \psi(e)] - \lambda U.$

4.2.2.4. The complete information case

Under complete information – with both β and e observable to both parties – the government would make a take-it-or-leave-it offer to Statoil solving

(6) $\max_{\{U,e\}} \{ S - (1 + \lambda)[\beta - e - \psi(e)] - \lambda U \}$

subject to $U \geq 0$.

The solution of this program is

(7) $\psi'(e) = 1$ or $e \equiv e^*$

which indicates that the marginal disutility of effort, $\psi'(e)$, must be equal to marginal cost savings, 1, and

(8) $U = 0$ or $t = \psi(e)$

which indicates that the firm should receive no rent because of the existence of a shadow cost of public funds.

In this case, the government could offer a *fixed-price contract*:

$$t(C) = a - (C - C^*)$$

where $a \equiv \psi(e^*)$ and $C^* \equiv \beta - e^*$.

As Statoil is residual claimant, they would choose the level of effort that maximizes $t(C)$, which is e^*. Their utility is then $U = 0$.

Note that this contract shows that the government need not observe effort. As long as they know β, they can infer effort $e = \beta - C$ from the observation of costs.

4.2.2.5. The two-type case

Now, I assume that the government knows that β, which characterizes Statoil's technological possibilities, and thus Statoil's type, can take two values: β_1 or β_2. In realistic to assume that the government has knowledge about an interval of values that β might take, but I choose to consider the two-type case for simplicity. The inefficient type that gives high costs, β_2, is larger than β_1. Let $\Delta\beta \equiv \beta_2 - \beta_1$.

The government observes the costs C and makes a net transfer t to Statoil. A contract between the two parties can be based on these jointly observed variables, one for each type of technology parameter: $t(\beta_1)$, $C(\beta_1)$ for the efficient, and $t(\beta_2)$, $C(\beta_2)$ for the inefficient. Let $t_1 \equiv t(\beta_1)$ and $t_2 \equiv t(\beta_2)$, and $C_1 \equiv C(\beta_1)$ and $C_2 \equiv C(\beta_2)$. Let $U(\beta) \equiv t(\beta) - \psi(\beta - C(\beta))$ denote the utility or rent of type β when it selects the transfer-cost pair designed for it. This gives $U_1 \equiv t_1 - \psi(\beta_1 - C_1)$ for the efficient and $U_2 \equiv t_2 - \psi(\beta_2 - C_2)$ for the inefficient type.

Incentive compatibility says that the contract designed for type β_1 is the one preferred by this type, and vice versa. Remembering that (1) $C = \beta - e$, the incentive compatibility constrains amounts to

$$(9)\quad t_1 - \psi(\beta_1 - C_1) \geq t_2 - \psi(\beta_1 - C_2)$$

$$(10)\quad t_2 - \psi(\beta_2 - C_2) \geq t_1 - \psi(\beta_2 - C_1)$$

where (9) says that it should not be profitable for the efficient type to pretend to be inefficient and (10) says that it should not be profitable for the inefficient type to pretend to be efficient.

The participation constraints for each type amounts to

(11) $U_1 \geq 0$

(12) $U_2 \geq 0$

It can be shown that since the efficient type always can mimic the inefficient one at a lower cost, (11) can be ignored. This leaves the participation constraint for the inefficient type to be only one that has to be taken into account.

The ex post social welfare when Statoil has type β becomes

$$W(\beta) = S - (1 + \lambda)[t(\beta) + C(\beta)] + t(\beta) - \psi(\beta - C(\beta))$$

$$= S - (1 + \lambda)[C(\beta) + \psi(\beta - C(\beta))] - \lambda U(\beta)$$

The government has a prior distribution on the values of β characterized by $v = \Pr(\beta = \beta_1)$ and selects the contract that maximizes expected social welfare $W \equiv vW(\beta_1) + (1 - v)W(\beta_1)$ under the incentive compatibility and participation constraints. When doing this, (10) can be neglected. It can be shown that the solution of the maximization problem will satisfy this. Hence, only the participation constraint for the inefficient type, (12), and the incentive compatibility constraint for the efficient one, (9), are retained. The latter can be rewritten

$$U_1 \geq t_2 - \psi(\beta_1 - C_2)$$

$$\geq U_2 + \Phi(e_1)$$

where $\Phi(e) \equiv \psi(e) - \psi(e - \Delta\beta)$ and $e_1 \equiv \beta_1 - C_1$. Since $\psi'' > 0$, $\Phi(\cdot)$ is increasing. This function plays a crucial role in what follows. It determines the rent of the efficient type of firm (relative to the inefficient type) by measuring the economy in disutility of effort associated with a better technology. The implication of the property $\Phi(\cdot)$ is increasing is that Statoil derives more informational rents under a high-powered incentive scheme (inducing high effort) than under a low-powered one.

The government's optimization problem is

(13) $\max_{\{C1,C2,U1,U2\}} \{\nu[S - (1 + \lambda)[C_1 + \psi(\beta_1 - C_1)] - \lambda U_1] + (1 - \nu)[S - (1 + \lambda)[C_2 + \psi(\beta_2 - C_2)] - \lambda U_2]\}$

subject to (9) and (12). Since the rents $U(\beta)$ are costly to the government, these constraints will be binding at the optimum. Substituting $U_2 = 0$ and $U_1 = \Phi(\beta_1 - C_1)$, we obtain

(14) $\psi'(\beta_1 - C_1) = 1$ or $e_1 = e^*$

(15) $\psi'(\beta_2 - C_2) = 1 - (\lambda /(1 + \lambda))(\nu/(1 - \nu))\Phi'(\beta_2 - C_2)$, implying that $e_2 < e^*$.

4.2.2.6. Results

For S large enough, that ensures that it is worth realizing the project even if Statoil is of the inefficient type, and $\psi''' \geq 0$, the optimal regulation under incomplete information is characterized by (14) and (15). It entails

- an efficient level of effort and a positive rent for Statoil if efficient

- undereffort and no rent for Statoil if inefficient

The ability of the efficient type to mimic the inefficient type forces the regulator to give up a rent to the efficient type if they wish to have an active inefficient type. The rent $\Phi(e_1)$ is a function of the effort level required from the *inefficient* type. If the regulator were to insist on the first-best level of effort, or $C_2 = \beta_2 - e^*$, the result would be a high rent for the efficient type since $\Phi' > 0$. To reduce the costly rent, the regulator lowers the effort level requested from the inefficient type.

By offering a fixed-price contract that ensures $e_1 = e^*$ and an incentive contract that ensures $e_2 < e^*$, the government could make the best out of the agreement, given the existence of the asymmetric information problem.

In general, asymmetric information forces the regulator to give up costly rent to their agents. To mitigate these costs, allocations are distorted away from first-best allocations and toward low-powered schemes. These distortions constitute the regulatory response to the asymmetry of information.

4.2.2.7. Discussion

It might seem tempting for the government to require the appropriate effort level if it observes that Statoil chooses the contract constructed for the inefficient type. However, this would be in conflict with the assumption that an enforceable contract can be made, and would not be consistent with the analysis. The contract for the inefficient type is constructed such that $U = 0$, which implies that requiring more costly effort from Statoil would leave them with $U < 0$, and make them break the contract.

To avoid giving up rents to the efficient type, the regulator can decide to go ahead with the project only if the cost is sufficiently low, which implies to only offer a contract designed for the efficient type. This would be an alternative if the S is not too high. Here, this means to offer a contract $\{t = \psi(e^*), C = \beta_1 - e^*\}$, and extract all the rents from the efficient type as it can no longer mimic the inefficient one. This would lead to a cancellation of the CCS project at Mongstad if Statoil does not have an efficient technology. Given the political difficulties when it comes to this project, this does not seem to be a realistic alternative.

Note that the optimal cost-reimbursement rule still requires substantial information. This might explain why we do not observe regulators offering menus of contracts in practice.

4.3 The actual contract

The actual contract is not optimal according to the previous analysis. First, only one contract is offered Statoil, and not a menu of contracts as the model suggested. However, only the final contract signed by Statoil is an official document, and not the bargaining process that gave rise to the contract.

The technology and the corresponding budgeted costs of the carbon capture facility at Mongstad will be agreed upon by the two parties after the contract is signed, but before the building starts. The government will pay for the investment costs of the carbon capture facility. Statoil will contribute with the amount corresponding to the CO_2 cost of their emissions. This cost will not depend on the total costs of the project at all. In addition, if the total costs exceed the budget, Statoil has to pay these exceeding costs. This means that Statoil has to undertake no risk up to a certain threshold, and all of the risk thereafter. This means that the contract is a *cost-plus contract* with a ceiling on the transfers from the government. Consequently, Statoil will have full incentives to avoid the costs from exceeding the budget, but no incentives to minimize the costs further.

Although this ceiling might resemble a *fixed-price contract*, it might have a perverse effect because Statoil could have the incentives to maximize the budgeted investment cost, or choose the technology they are most familiar with and have the most private information about. If they are better informed than the government, they would like to maximize the difference between what they consider to be the expected costs, and what they can convince the government to be the expected costs. This is to minimize the likelihood of having to pay for exceeding costs.

For example, let Statoil have the choice between two technologies that have the same expected costs, but one is riskier and has a larger $\Delta\beta$. Statoil would then choose the least risky technology: the expected costs for *them* will not be the same since they will not benefit from the reduced costs if the technology turns out to be very efficient, but suffer from the extra costs if it turns out to be inefficient. This would also be true for two technologies with differing expected costs, where the expected costs of the risky one is the lowest. The government would have wanted the risky technology to be chosen, but Statoil will not choose this.

A technology company will be established and will run a test centre for various carbon capture technologies. Statoil will own 20 %, the remaining 80 % will be guaranteed by the government, by direct ownership and/or by recruiting other firms to join. The technology company can be thought of as a way to reduce Statoil's private information about this project. In the model discussed above, this could translate into reducing $\Delta\beta$ .The experience will be shared between the firms involved in this company. This might be compatible with the government's vision of making this available, but might not be in Statoil's interest. They will not be the only firm gaining this experience, and will be less able to extract rent from the government because of the asymmetric information about β.

Any revenue from a potential CO_2 value chain will be deducted from the government's costs. Considering the potential problems with such a value chain as discussed in chapter 4.1., it might have been a good idea to let Statoil benefit from such revenues, giving them more incentives to coordinate their projects with other firms.

5. Conclusion

Whether this project should be carried out or not, is difficult to say and to do so is not the intention of this thesis. I have shown that this depends on the costs of carbon capture and storage compared to other mitigation strategies, and how steep the learning curve of this new and uncertain technology is. The question is whether investing in CCS will bring down the future costs enough to defend the choice of such a costly mitigation strategy.

The existence of information asymmetry, and therefore lack of incentives to invest in CCS is one of the factors that might justify the governmental involvement in this project, as I discussed in chapter 4.1. The very existence of information asymmetry and incentive problems, however, might keep the project from being carried out in an efficient manner, as I discussed in chapter 4.2.

In reality, it is difficult to predict where the asymmetry lies, and hence what policy will be the most effective. Even though the actual contract does not leave Statoil completely without incentives, a better contract could probably be made by making Statoil's contribution more dependent on total costs.

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Appendix 1: Assumptions and calculations

Most data and assumption are taken from Reinaud, 2003, with the exception of fuel-prices, taken from IEA 2006, and the CCS assumptions, which are taken from IPCC, 2005.

Input data used:

	Thermal Efficiency %	Fuel price €/GJ	Economic plant life yrs	Variable O&M costs €cents/kWh	Fixed O&M costs €cents/kWh	Investment costs €/MW	Carbon content tC/TJ
Existing coal-fired plant	37	1,7		0,33	0,23		25,8
New coal-fired plant	40	1,7	30	0,33	0,23	1100	25,8
Existing gas-fired plant	49	3,5		0,15	0,35		15,3
New gas-fired plant	55	3,5	25	0,15	0,35	500	15,3
Discount rate	7 %						
Plant availability	80 %						

Fuel prices:

Coal price: 1.7 €/GJ

Gas price: 4.5 €/GJ

Explanations to the formulas in the following spread sheet:

Fuel cost = (fuel price at plant*conversion GJ to MWh 3,6)/thermal efficiency

Amount of CO_2 emitted = (emission rate for coal* conversion TJ to MWh 0,0036*conversion rate C to CO_2 (44/12))/thermal efficiency

CO_2 cost = amount of CO_2 emitted*CO_2 price

Cost of capital = ((capital costs/plant capacity)*annuity)/(hours a year 8750*plant availability)

Annuity = $r/(1-(1/(1+r)^n))$

SRMC (short run marginal cost or ex post cost) = fuel cost + variable O&M cost (+ CO_2 cost)

LRMC (long run marginal cost or ex ante cost) = fuel cost + variable O&M cost + fixed O&M cost + cost of capital (+CO_2 cost)

Copy of spread sheet I used to calculate marginal costs:

Coal-Fired Power Plants		
Without CCS		
SHORT RUN - EX POST		
Fuel price at plant	**€/GJ**	**1,70**
Fuel cost	**€/MWh**	**16,54**
Variable O&M cost	**€/MWh**	**3,33**
Thermal efficiency	**%**	**37 %**
SRMC (no CO2 price)	**/MWh**	**19,87**
Emission rate for coal	**tC/TJ**	**25,8**
Amount of CO2 emitted	**tCO2/MWh**	**0,92**
CO2 price	**€/t**	**100**
CO2 cost	**€/MWh**	**92,04**
SRMC with CO2 price)	**/MWh**	**111,91**
LONG RUN - EX ANTE		
Plant capacity	**MW**	**740**
Capital costs	**€**	**825000000**
Economic Plant Life - n	**yrs**	**30**
Plant availability	**%**	**80 %**
Fuel Price	**€/GJ**	**1,70**
Fuel Costs	**€/MWh**	**15,30**
Cost of Capital	**€/MWh**	**12,83**
Variable O&M Costs	**€/MWh**	**3,33**
Fixed O&M Costs	**€/MWh**	**3,50**
Thermal efficiency	**%**	**40 %**
Annuity/pretax return	**%**	**8,06 %**
Depreciation	**€/MWh**	**5,23**
LRMC (no CO2 price)	**/MWh**	**34,96**
Amount of CO2 emitted	**tCO2/MWh**	**0,8514**
CO2 price	**€/t**	**100**
CO2 cost	**€/MWh**	**85,14**
LRMC (with CO2 price)	**/MWh**	**120,10**

Results from spread sheet: marginal costs at various CO2 prices without CCS:

		CO2 prices:			
	Fuel price:	0	20	50	100
Existing coal-fired plant	1,7	1,99	3,83	6,59	11,19
Existing gas-fired plant	4,5	3,46	4,28	5,52	7,58
New coal-fired plant	1,7	3,5	5,2	7,75	12,01
New gas-fired plant	4,5	3,94	4,68	5,78	7,61

CCS assumptions:

	EC	EG*	NC	NG
Capture costs CCS	3,50	4,00	1,30	1,50

* as the capture cost for existing gas-fired plants was not given in the IPPC report, I added a cost based on my own assumption: I assume that since since it is more expensive to retrofit an existing plant, and that CCS on gas-fired plants is more expensive than on coal-fired ones, it is reasonable to assume that . I took the cost of new gas-fired plants, and added a extra cost equivalent to the percentage difference in costs between new and existing coal plants.

	$/tCO2	€/tCO2**	€cents/tCO2	Mid-point: €cents/tCO2
Transportation costs	0 - 5	0 - 3,9	0 - 390	200
Geological storage	0,6 - 8,3	0,5 - 6,4	50 - 640	350

** Assumption: 1 € = 1,3 $

I've used the last column in my analysis;
this corresponds to a mid-point of the range of costs reported in IPCC 2005.

	Emissions tCO2/MWh	Emissions tCO2/kWh	Tr.cost €cents/kWh	St.cost €cents/kWh	EOR €cents/kWh	Total (geo) €cents/kWh
Existing coal-fired plant	0,18	0,00018409	0,04	0,06	-0,18	0,1
New coal-fired plant	0,17	0,00017028	0,03	0,06	-0,17	0,09
Existing gas-fired plant	0,08	8,24E-05	0,02	0,03	-0,08	0,05
New gas-fired plant	0,07	0,00007344	0,01	0,03	-0,07	0,04

	EC	EG	NC	NG
Increased cost w/ CCS*	3,50	4,00	1,30	1,50
Transport + geo. storage	0,10	0,05	0,09	0,04
Total w/ geo. storage	3,60	4,05	1,39	1,54

CCS: new marginal costs at different CO_2-prices:

CO2 prices:	0	20	50	100
Existing coal-fired plant				
MC no CCS/no CO2 price	1,99	1,99	1,99	1,99
CO2-cost w/ CCS	0,00	0,37	0,92	1,84
Increased cost w/ CCS	3,60	3,60	3,60	3,60
MC with CCS	5,59	5,96	6,51	7,43
Existing gas-fired plant				
MC no CCS/no CO2 price	2,72	2,72	2,72	2,72
CO2-cost w/ CCS	0,00	0,16	0,41	0,82
Increased cost w/CCS	4,05	4,05	4,05	4,05
MC with CCS	6,77	6,93	7,18	7,59
New coal-fired plant				
MC no CCS/no CO2 price	3,50	3,50	3,50	3,50
CO2-cost w/ CCS	0,00	0,34	0,85	1,70
Increased cost w/ CCS*	1,39	1,39	1,39	1,39
MC with CCS	4,89	5,23	5,74	6,59
New gas-fired plant				
MC no CCS/no CO2 price	3,29	3,29	3,29	3,29
CO2-cost w/ CCS	0,00	0,15	0,37	0,73
Increased cost w/ CCS*	1,54	1,54	1,54	1,54
MC with CCS	4,83	4,98	5,20	5,56

Appendix 2: List of abbreviations and symbols

CCS	carbon capture and storage
CO_2	carbon dioxide
EOR	enhanced oil recovery
EC	Existing coal-fired plant
EG	Existing gas-fired plant
EC CCS	Existing coal-fired plant with CCS
EG CCS	Existing gas-fired plant with CCS
EU ETS	European Union's Emission Trading Scheme
IEA	International Energy Agency
IPCC	International Panel on Climate change
kWh	kilowatt hours
NC	New coal-fired plant
NC CCS	New coal-fired plant with CCS
NG	New gas-fired plant
NG CCS	New gas-fired with CCS
NPD	Norwegian Petroleum Directorate
NVE	Norwegian Water Resources and Energy Directorate
O&M	operation and maintenance
tCO_2	ton carbon dioxide
TJ	terrajoule
WEC	World Energy Council
C	the cost of the CCS project
β	the efficiency parameter
e	Statoil's effort
U	Statoil's utility function
$\psi(e)$	Statoil's disutility from exerting effort
t	transfer from the government to Statoil
λ	shadow cost of public funds
S	value of the CCS project for consumers
v	probability of high efficiency parameter