**Norwegian University of
Science and Technology
NTNU**

**Faculty of Social Science and
Technology Management**

Department of Industrial Economics and Technology Management

MASTER THESIS

for

STUD.TECHN. KRISTIN BECKSTRØM, KRISTIN LIEN AND MARTE AABERG

Field of study	**Managerial Economics and Operations Research** Anvendt økonomi og optimering
Start date	15th of January 2008
Title	**Optimization of CO2 Value Chains** Optimering av CO2-verdikjeden
Purpose	CO2 can be injected into oil and gas fields for a 5 to 15% (ref. Oil-in-place) increased petroleum recovery, extending the lifetime of the fields. Alternatively, CO2 can be stored in aquifers without EOR/EGR. This thesis will perform technical-economical analyses for enhancing the decision making process, under uncertainty, for the development of a new value chain with CO2 from power plants into operated oil and gas fields.

Main contents:

1. Identify, analyse and model the main uncertainties affecting the problem, focusing on economic and cost factors, including the development over time.
2. Evaluation and analysis of relevant parts of the CO2 value chains.

Tim Torvatn
Department Management

Stein-Erik Fleten
Stein-Erik Fleten
Supervisor

NTNU

STANDARDAVTALE

Avtale mellom student...Marte Aaberg..........................**født**...17-04.82**,**

faglærer ved NTNU...Stein-Erik Fleten..................................**,**

bedrift/institusjon...StatoilHydro..**og**

Norges teknisk-naturvitenskapelige universitet (heretter NTNU) v/representant for instituttledelsen om bruk og utnyttelse av spesifikasjoner og resultater fremlagt ved besvarelse av masteroppgave i henhold til Utfyllende regler til studieforskriften for teknologistudiet/sivilingeniørstudiet ved NTNU, vedtatt av Styret for sivilingeniørutdanningen 28.04.03.

1. Studenten skal utføre besvarelse av den tildelte masteroppgave ved:

   ...StatoilHydro...(bedrift/institusjon).

   Oppgavens tittel er: ....Optimization....of.....CO_2....Value.....Chains

   ....

2. Studenten har opphavsrett til besvarelsen. De innleverte eksemplarer av besvarelsen med tegninger, modeller og apparatur, så vel som dataprogramvare som inngår som del av eller vedlegg til besvarelsen, tilhører NTNU. Besvarelsen, og vedlegg til denne, kan vederlagsfritt benyttes av NTNU til undervisnings- og forskningsformål. Besvarelsen, og vedlegg til denne, må ikke nyttes til andre formål.

3. Studenten har rett til å publisere sin besvarelse, eller deler av den, som en selvstendig avhandling eller som del av et større arbeid, eller i popularisert form i hvilken som helst offentlig publikasjon.

4. Bedriften/institusjonen har rett til å få utlevert et eksemplar av besvarelsen med vedlegg, og til å gjøre seg kjent med NTNU's bedømmelse av den. Bedriften/institusjonen gis en frist på 3 måneder fra besvarelsen er innlevert til NTNU for sensurering til å vurdere patenterbarhet og søke patent på hele eller deler av resultatet av besvarelsen. Besvarelsens spesifikasjoner og resultater kan bedriften/institusjonen nytte i sin egen virksomhet. Dersom besvarelsens spesifikasjoner og resultater skal utnyttes økonomisk av bedriften/institusjonen, må det inngås særskilt avtale med alle parter. NTNU's tilleggsavtale om økonomisk utnyttelse skal da benyttes. Avtale om økonomisk utnyttelse

opprettes i 4 - fire eksemplarer hvor partene skal ha hvert sitt og er gyldig når den er godkjent og underskrevet av NTNU v/representant for instituttledelsen.

5. I særlige tilfelle kan offentliggjørelsen av besvarelsen i samsvar med pkt. 2 og 3 ovenfor båndlegges (utsettes) for en periode på inntil 5 år. Det skal i slike tilfelle inngås en egen båndleggelsesavtale mellom student, faglærer, bedrift/institusjon og NTNU. NTNU's tilleggsavtale om båndlegging skal da benyttes. Båndleggelsesavtalen opprettes i 4 - fire eksemplarer hvor partene skal ha hvert sitt og er gyldig når den er godkjent og underskrevet av NTNU v/representant for instituttledelsen.

6. Denne avtale skal ha gyldighet foran andre avtaler som er eller blir opprettet mellom to av partene som er nevnt ovenfor.

7. Eventuell uenighet som følge av denne avtale skal søkes løst ved forhandlinger. Hvis dette ikke fører frem, er partene enige om å la tvisten avgjøres ved voldgift i henhold til norsk lov. Tvisten avgjøres av sorenskriveren ved Trondheim tingrett eller den han/hun oppnevner.

8. Denne avtale er underskrevet i 4 - fire - eksemplarer hvor partene skal ha hvert sitt. Avtalen er gyldig når den er godkjent og underskrevet av NTNU v/representant for instituttledelsen.

Trondheim
(sted)

30.01.08
(dato)

student

Stein-Erik Fleten
faglærer ved NTNU

Tore A. Torp

StatoilHydro ASA

for bedriften/institusjonen
(stempel og signatur)

Avtalen godkjennes:

21/5-08

NTNU
Institutt for industriell økonomi
og teknologiledelse
7491 TRONDHEIM

Representant for instituttledelsen, NTNU (dato, stempel og signatur)

NTNU

STANDARDAVTALE

Avtale mellom student........Kristin Ljønes........**født**..26.06.82..

faglærer ved NTNU........Stein-Erik Fleten........**,**

bedrift/institusjon........StatoilHydro........**og**

Norges teknisk-naturvitenskapelige universitet (heretter NTNU) v/representant for instituttledelsen om bruk og utnyttelse av spesifikasjoner og resultater fremlagt ved besvarelse av masteroppgave i henhold til Utfyllende regler til studieforskriften for teknologistudiet/sivilingeniørstudiet ved NTNU, vedtatt av Styret for sivilingeniørutdanningen 28.04.03.

1. Studenten skal utføre besvarelse av den tildelte masteroppgave ved:

   StatoilHydro........(bedrift/institusjon).

   Oppgavens tittel er: ..Optimization of CO_2 Value Chains........

   ....

2. Studenten har opphavsrett til besvarelsen. De innleverte eksemplarer av besvarelsen med tegninger, modeller og apparatur, så vel som dataprogramvare som inngår som del av eller vedlegg til besvarelsen, tilhører NTNU. Besvarelsen, og vedlegg til denne, kan vederlagsfritt benyttes av NTNU til undervisnings- og forskningsformål. Besvarelsen, og vedlegg til denne, må ikke nyttes til andre formål.

3. Studenten har rett til å publisere sin besvarelse, eller deler av den, som en selvstendig avhandling eller som del av et større arbeid, eller i popularisert form i hvilken som helst offentlig publikasjon.

4. Bedriften/institusjonen har rett til å få utlevert et eksemplar av besvarelsen med vedlegg, og til å gjøre seg kjent med NTNU's bedømmelse av den. Bedriften/institusjonen gis en frist på 3 måneder fra besvarelsen er innlevert til NTNU for sensurering til å vurdere patenterbarhet og søke patent på hele eller deler av resultatet av besvarelsen. Besvarelsens spesifikasjoner og resultater kan bedriften/institusjonen nytte i sin egen virksomhet. Dersom besvarelsens spesifikasjoner og resultater skal utnyttes økonomisk av bedriften/institusjonen, må det inngås særskilt avtale med alle parter. NTNU's tilleggsavtale om økonomisk utnyttelse skal da benyttes. Avtale om økonomisk utnyttelse

opprettes i 4 - fire eksemplarer hvor partene skal ha hvert sitt og er gyldig når den er godkjent og underskrevet av NTNU v/representant for instituttledelsen.

5. I særlige tilfelle kan offentliggjørelsen av besvarelsen i samsvar med pkt. 2 og 3 ovenfor båndlegges (utsettes) for en periode på inntil 5 år. Det skal i slike tilfelle inngås en egen båndleggelsesavtale mellom student, faglærer, bedrift/institusjon og NTNU. NTNU's tilleggsavtale om båndlegging skal da benyttes. Båndleggelsesavtalen opprettes i 4 - fire eksemplarer hvor partene skal ha hvert sitt og er gyldig når den er godkjent og underskrevet av NTNU v/representant for instituttledelsen.

6. Denne avtale skal ha gyldighet foran andre avtaler som er eller blir opprettet mellom to av partene som er nevnt ovenfor.

7. Eventuell uenighet som følge av denne avtale skal søkes løst ved forhandlinger. Hvis dette ikke fører frem, er partene enige om å la tvisten avgjøres ved voldgift i henhold til norsk lov. Tvisten avgjøres av sorenskriveren ved Trondheim tingrett eller den han/hun oppnevner.

8. Denne avtale er underskrevet i 4 - fire - eksemplarer hvor partene skal ha hvert sitt. Avtalen er gyldig når den er godkjent og underskrevet av NTNU v/representant for instituttledelsen.

Trondheim .... (sted)

30.01.08 .... (dato)

Kristin Ljones .... student

Stein-Erik Fleten .... faglærer ved NTNU

Tore A. Torp ....

StatoilHydro ASA ....

for bedriften/institusjonen
(stempel og signatur)

Avtalen godkjennes:

21/5-09 ....

Representant for instituttledelsen, NTNU (dato, stempel og signatur)

NTNU
Institutt for industriell økonomi
og teknologiledelse
7491 TRONDHEIM

NTNU

STANDARDAVTALE

Avtale mellom student..Kristin Lien..**født**.29.08.82,

faglærer ved NTNU...Steen-Erik Fleten..,

bedrift/institusjon...StatoilHydro..**og**

Norges teknisk-naturvitenskapelige universitet (heretter NTNU) v/representant for instituttledelsen om bruk og utnyttelse av spesifikasjoner og resultater fremlagt ved besvarelse av masteroppgave i henhold til Utfyllende regler til studieforskriften for teknologistudiet/sivilingeniørstudiet ved NTNU, vedtatt av Styret for sivilingeniørutdanningen 28.04.03.

1. Studenten skal utføre besvarelse av den tildelte masteroppgave ved:

   StatoilHydro..(bedrift/institusjon).

   Oppgavens tittel er: ..Optimization of CO2 Value Chains...

   ....

2. Studenten har opphavsrett til besvarelsen. De innleverte eksemplarer av besvarelsen med tegninger, modeller og apparatur, så vel som dataprogramvare som inngår som del av eller vedlegg til besvarelsen, tilhører NTNU. Besvarelsen, og vedlegg til denne, kan vederlagsfritt benyttes av NTNU til undervisnings- og forskningsformål. Besvarelsen, og vedlegg til denne, må ikke nyttes til andre formål.

3. Studenten har rett til å publisere sin besvarelse, eller deler av den, som en selvstendig avhandling eller som del av et større arbeid, eller i popularisert form i hvilken som helst offentlig publikasjon.

4. Bedriften/institusjonen har rett til å få utlevert et eksemplar av besvarelsen med vedlegg, og til å gjøre seg kjent med NTNU's bedømmelse av den. Bedriften/institusjonen gis en frist på 3 måneder fra besvarelsen er innlevert til NTNU for sensurering til å vurdere patenterbarhet og søke patent på hele eller deler av resultatet av besvarelsen. Besvarelsens spesifikasjoner og resultater kan bedriften/institusjonen nytte i sin egen virksomhet. Dersom besvarelsens spesifikasjoner og resultater skal utnyttes økonomisk av bedriften/institusjonen, må det inngås særskilt avtale med alle parter. NTNU's tilleggsavtale om økonomisk utnyttelse skal da benyttes. Avtale om økonomisk utnyttelse

opprettes i 4 - fire eksemplarer hvor partene skal ha hvert sitt og er gyldig når den er godkjent og underskrevet av NTNU v/representant for instituttledelsen.

5. I særlige tilfelle kan offentliggjørelsen av besvarelsen i samsvar med pkt. 2 og 3 ovenfor båndlegges (utsettes) for en periode på inntil 5 år. Det skal i slike tilfelle inngås en egen båndleggelsesavtale mellom student, faglærer, bedrift/institusjon og NTNU. NTNU's tilleggsavtale om båndlegging skal da benyttes. Båndleggelsesavtalen opprettes i 4 - fire eksemplarer hvor partene skal ha hvert sitt og er gyldig når den er godkjent og underskrevet av NTNU v/representant for instituttledelsen.

6. Denne avtale skal ha gyldighet foran andre avtaler som er eller blir opprettet mellom to av partene som er nevnt ovenfor.

7. Eventuell uenighet som følge av denne avtale skal søkes løst ved forhandlinger. Hvis dette ikke fører frem, er partene enige om å la tvisten avgjøres ved voldgift i henhold til norsk lov. Tvisten avgjøres av sorenskriveren ved Trondheim tingrett eller den han/hun oppnevner.

8. Denne avtale er underskrevet i 4 - fire - eksemplarer hvor partene skal ha hvert sitt. Avtalen er gyldig når den er godkjent og underskrevet av NTNU v/representant for instituttledelsen.

Trondheim .... 30.01.08 ....

(sted) (dato)

Kristin Lien .... Stein-Erik Fleten .... Tore A. Torp ....

student faglærer ved NTNU

StatoilHydro ASA

....

for bedriften/institusjonen
(stempel og signatur)

Avtalen godkjennes:

NTNU
Institutt for industriell økonomi
og teknologiledelse
7491 TRONDHEIM

21/5-08 ....

Representant for instituttledelsen, NTNU (dato, stempel og signatur)

DECLARATION

Stud.techn. ____

Institute of Industrial Economy and Technology Management

I hereby declare that I have written the above mentioned
thesis without any kind of illegal assistance

________________________ ________________________

Place Date

____

Signature

In accordance with Examination regulations § 20, this thesis, together with its figures etc., remains the property of the Norwegian University of Science and Technology (NTNU).
Its contents, or results of them, may not be used for other purpose without the consent of the interested parties.

DECLARATION

Stud.techn. ______________________________
Institute of Industrial Economy and Technology Management

I hereby declare that I have written the above mentioned
thesis without any kind of illegal assistance

______________________ Place

______________________ Date

______________________________ Signature

In accordance with Examination regulations § 20, this thesis, together with its figures etc., remains the property of the Norwegian University of Science and Technology (NTNU).
Its contents, or results of them, may not be used for other purpose without the consent of the interested parties.

DECLARATION

Stud.techn. ____
Institute of Industrial Economy and Technology Management

I hereby declare that I have written the above mentioned
thesis without any kind of illegal assistance

________________________ ________________________
Place Date

____
Signature

In accordance with Examination regulations § 20, this thesis, together with its figures etc., remains the property of the Norwegian University of Science and Technology (NTNU). Its contents, or results of them, may not be used for other purpose without the consent of the interested parties.

Preface

This master thesis was written during the spring of 2008 at the Norwegian University of Science and Technology (NTNU), Department of Industrial Economics and Technology Management within the field of study Managerial Economics and Operations Research. The idea behind the thesis originates from the European value chain for CO_2 project (ECCO), and was accomplished in cooperation with StatoilHydro ASA.

We would like to thank our supervisor, associate professor Stein-Erik Fleten (NTNU), for good support, interesting discussions and constructive feedback throughout the work. We would also like to express our gratitude towards Tore Torp (StatoilHydro ASA) for having provided valuable information and productive advice, and for inviting us to attend the CO_2NET Annual Seminar in Warsaw in April 2008 where we had the chance to gain insight into the current status for carbon capture and storage. It was very motivating for the work with this thesis. Finally, we would like to thank Petter Røkke (SINTEF) for giving his opinions on the subject.

Trondheim, May 30th 2008

Marte Aaberg

Kristin Ljønes

Kristin Lien

Summary

This thesis evaluates the investment timing decisions in a CO_2 value chain with enhanced oil recovery (EOR), where CO_2 captured at a gas power plant is either employed for EOR or stored permanently in a reservoir. There are two commercial incentives for creating such value chains. Firstly, carbon emission costs may be omitted by capturing the CO_2. Secondly, revenues may be obtained if extra oil is recovered.

The presented value chain corresponds to a simplification of a potential Norwegian value chain with a capture plant at Tjeldbergodden gas power plant, EOR facilities at the Heidrun production field and storage possibilities in a nearby saline formation, referred to as the Alpha structure. The model is divided into two investment projects. The capture investment project requires investments in capture plant, pipelines and storage facilities. The EOR investment may only be carried out if the capture investment is implemented, and includes EOR facilities and separation facilities.

In order to include flexibility and uncertainty, the investment projects are treated as real options, which are modelled in a stochastic dynamic program (SDP). The dynamic property refers to the timing flexibility of the investment decisions, whereas the stochastic property refers to the implementation of uncertainty for crude oil and carbon prices. These prices are modelled by means of a non-rectangular, tree which is based on the theory of binomial trees and integrates for the correlation between the two prices.

In addition to anaysing the investment decision strategies indicated by the SDP, analysis regarding random price realizations are carried out by means of Monte Carlo simulations.

Based on the analysis, it appears to be very likely that it will be significantly better to invest in both capture and EOR than not investing at all. With respect to the timing, it is clear that the projects should be undertaken as late as possible. Investing in the capture project exclusively, which corresponds to a capture and storage solution, will not be optimal within the investigated price ranges. If both crude oil and carbon prices turn out to be extremely low, no investments should be implemented.

These observations rest on the fact that the second incentive (EOR revenues) controls both decisions. As the capture project never is optimal without EOR and hardly ever will be optimal earlier than the EOR project, avoiding carbon costs is not an incentive for CO_2 capture with the applied carbon costs.

Contents

List of Figures

List of Tables

1 Introduction

Carbon dioxide emissions have over the last decades become an issue of large attention. The IPCC Third Assessment Report claims that the climate changes are caused by humans. Discussions are proceeding concerning how the humans are to cope with the impacts of the greenhouse effect, to which CO_2 contributes to a large extent. Energy use constitutes 65% of the emissions through the combustion of fossil fuels, and initiatives on coping with this problem include elements like increased energy efficiency and a switch to other sources of energy such as renewables. According to IPCC the global CO_2 emissions need to be reduced by 50-58% within 2050 in order for hazardous climate changes to be avoided. EU has set ambitious goals to reach this target.

Norway also takes action, and has made commitments through the Kyoto protocol. In the period 2008-2012 the climate gas emissions in Norway should not increase by more than 1%, compared to the emission level of 1990. Nationally, petroleum operations account for 27% of CO_2 emissions. It is argued that, to be able to meet the increasing world energy demand, fossil fuels are still needed. Norway anyhow needs to take responsibility for the climate damages caused by its power sector. CO_2 capture and storage is seen as a way to keep using fossil fuels and at the same time take responsibility concerning emissions.

A range of studies have been carried out on possible CO_2 value chains connected to natural gas power plants. Using CO_2 for enhanced oil recovery (EOR) is often added as an attempt of making the CO_2 generate additional profit. CO_2 is injected into the oil field to enable the extraction of about 5-15% more of the original oil in place. The profitability of the value chain investigated in these studies is nevertheless missing, as the net present values (NPVs) of the projects are in the majority of the cases calculated to be negative.

Profitability studies based on the NPV method incorporate weaknesses. Firstly, they often omit uncertainty. Uncertain input parameters such as energy prices and technology costs are often set to be deterministic far into the future. Could the stochastic nature of these values imply alterations in the outcome of the investment decisions? Secondly, they do not investigate whether the timing of the investments affect the profitability. At what points in time should CO_2 be captured, used for storage, and what time is the optimal time for using it for EOR? In a usual NPV calculation the value of flexibility lacks consideration.

In this thesis a stochastic dynamic program for a simplified CO_2 value chain is created in order to investigate the impacts of timing flexibility and price uncertainty on the profitability. The main objective is to:

> *Analyse the timing of investment decisions in a simplified CO_2 value chain with uncertainty in important economic factors.*

To reach this target the following elements are included:

- Study the selected CO_2 value chain, and make relevant assumptions
- Map, analyse and model the main uncertainties related to the problem
- Implement flexibility and uncertainty by using a real option approach to evaluate the profitability of the chain as a whole
- Analyse and discuss the results

We expect the model to point to the value of time in the investment process, and how the stochastic nature of important input parameters make an influence. An actual investment decision requires further study of input parameters and would need adjustments according to the system in question.

The structure of the thesis is as follows. The background and incentives for creating a CO_2 value chain are presented in section 2. Section 3 maps the uncertainties related to the such chains. Section 4 presents the value chain treated in this thesis and all the assumptions incorporated. The stochastic dynamic programming model and its states are described in section 5. Various quantitive results are to be found in section 6. A qualitative discussion concerning findings is found in 7. In section 8 criticism of the work is treated. Suggestions for further work are present in section 9. Finally in section 10 a conclusion is made upon the study implemented.

2 Background

This section starts out by explaining two commercial incentives for creating CO_2 value chains with enhanced oil recovery (EOR). The first incentive is related to carbon costs, whereas the second is connected to EOR. Furthermore, the technological elements which are included in such value chains are outlined. Finally, a status update on prevoius work concerning CO_2 value chains is given.

2.1 CO_2 capture and the European carbon market

We shall now explain the background for, the development of and the consequences of the introduction of CO_2 emission quotas. One of the commercial incentives of the creation of CO_2 value chains may be that of avoiding the cost of CO_2 emission by means of capturing and storing the CO_2 rather than emitting it.

In decision-making a profit-searching enterprise evaluates those operations which lead to revenues or costs. From a business perspective all other activities and their consequences are irrelevant. Such activities may however cause costs or benefits for others and are referred to as externalities. According to (Zerbe 1994) externalities are "*costs or benefits not reflected fully in decision making or in prices*". There are two main reasons for which externalities are not paid for. Firstly, "*for technological reasons it is too difficult to collect from potential payers.*" Secondly, "*the absence of ownership of other legal barrier does not allow collection for provision of the good.*" Emissions to air or water from industrial production and noise from transport are representative examples of such externalities. Both reasons stated above apply for emissions to air. For instance, it would be difficult to measure the exact amount of greenhouse gases that each car produced, and collecting a fee would not be impossible but yet require a vast system. Furthermore, emissions to air quickly spread over large areas and we are not used to thinking "Whose air am I polluting now?"

2.1.1 Carbon emissions as an externality

Carbon emissions have been a typical externality. Because this greenhouse gas has not been subject to cost or revenue generation, CO_2 emitting enterprises have not considered the emission or its impacts when making decisions. There have been no legal requirements or financial incentives for paying attention to emissions.[1] The emissions have however had a negative impact for the society, and those who are responsible have not compensated for these impacts. We will now attempt to explain how CO_2 production for a gas power plant has been changed from being an externality into a factor which will influence the profit of the producer and thereby its decision-making process.

---

[1] Norway introduced a public CO_2tax in 1991.

2.1.2 A commercial incentive for avoiding carbon emissions

As the disadvantages caused by CO_2 emissions have been observed, known and recognized, international initiative has been taken in order to reduce the emissions and thus mitigate climate change. As a result most nations have ratified the Kyoto protocol and are thereby obliged to follow a wide range of instructions concerning carbon emissions. One of the main features of the Kyoto protocol is the implementation of CO_2 emission quotas which is supposed to encourage emission reduction by means of financial incentives. For further insight in the Kyoto protocol and its mechanisms the reader is referred to information published by the United Naitons Framework Convetnion on Climate Change (UNFCCC) at their official internet site.[2]

The European approach to meeting the Kyoto Protocol

Norway ratified the Kyoto protocol in May 2002. In February 2005 enough states had signed the agreement for it to enter into force. In Phase I of the Kyoto protocol, which lasted from 2005 through 2007, 95% of the quotas were free[3] and there was a surplus of them. Each state is responsible for achieving its Kyoto goal. The member states of the European Union have transferred their commitments to private actors by creating the EU Emission Trading Scheme (EU ETS) where carbon emitters may trade emission quotas between them across state borders. The EU ETS was implemented in January 2005. In order to assimilate to the new global carbon regime, Norway created its own carbon market, corresponding to the EU ETS. This market was also implemented in January 2005. In Phase II, 2008-2012, there are less quotas, but more than 90% are still free. Norway joined EU ETS in January 2008. Different carbon emitting sectors are step-wise subject to emission reductions. A gas power plant, which is the carbon emitting unit in this thesis, is already affected by this scheme (Statkraft 2007).

It is not completely clear how carbon emissions will be dealt with after 2012. Decisions will be taken later based on present experience. However it seems clear that in order to achieve the goals set by the Kyoto Protocol commitments, stricter policies and further development of the carbon markets may occur. It is therefore reasonable to expect that carbon emissions from a gas power plant are subject to restrictions throughout the life time of the plant.

The cost of producing CO_2

According to the introduction of emission quotas, CO_2 represents a cost for the producer. Hence, a gas power plant needs to incorporate its CO_2 production in its decision-making processes. If CO_2 is captured and stored so that emissions

---

[2] http://unfccc.int/kyoto_protocol/items/2830.php

[3] Free quotas were/are given to emitting actors from the authorities. Received free quotas may then be traded between the actors. The fact that a quota may be sold, introduces the incentive for reducing emissions.

are avoided, the quota cost does not occur. This forms the commercial incentive for CO_2 producers to treat produced CO_2. The purchase cost of carbon emission quotas represents the cost of not capturing and storing CO_2.

In the carbon markets, the quota price is a result of demand and supply. For the market to serve its goal, namely emission reduction, it is essential that there is a quota deficit. The CO_2 quota price may be regarded as the cost society puts on emission impacts. If an enterprise pays the quota price, society is willing to accept the harm caused by the corresponding amount of CO_2. The enterprise buys the right to emit a certain amount of CO_2. This mechanism is based on the idea that some other actor is willing to reduce his emissions by the corresponding quota amount if he can avoid the cost of paying for that quota. In order to achieve an emission reduction down to a specific level, the quota price should correspond to a level which is high enough for CO_2 producers to carry out emission reducing measures. Even though it is beyond the scope of this thesis, it is important to note that such measures do not exclusively include CO_2 capture and storage. Among several other measures, they also include energy switch from fossil fuels, increasing energy efficiencies and energy consumption reducing measures.

2.2 The role of EOR in CO_2 value chains

In the previous sub-section we explained how CO_2 emission quotas form a commercial incentive for capture and storage CO_2 instead of emitting it. Another commercial incentive for capturing the CO_2, which will be described in this section, is its application as an EOR input factor. Whereas the first incentive originates from social regards and interests, the EOR based incentive is directly connected to an oil producer's wish to increase revenues by extracting more oil from production fields.

2.2.1 EOR as a commercial incentive

Oil may only be extracted from the fields until the pressure drops to a given reservoir level, or the field is producing too much water. Very roughly and dependent on the properties of the field, this level may be 40-60% of the original oil in place (OIIP). Thus, there are still significant amounts of oil, and hence revenue potential, left in the reservoir. Not surprisingly, great effort has been, and is, put into research concerning higher extraction rates. Pressure recovery by gas injection, water injection or alternating water and gas injection (WAG) are of common methods. All methods aim to regain reservoir pressure and displace oil for increased recovery. CO_2 may replace natural gas as injectant from production starts, or it may be employed after water injection. When water injection is no longer efficient in the field, CO_2 injection proves in many cases particularly useful due to its properties. When oil and CO_2 are mixed, the viscosity of the oil is reduced so that the interfacial tension between the phases is reduced. This causes oil displacement and is referred to as miscible displacement. The oil displacement causes more oil to flow and enables hence increased production. In reservoirs where miscibility is not obtained, CO_2 may still prove useful because it may reach parts of the reservoir and displace oil where other injectants would not reach (NVE 2005).

Clearly, this forms a commercial incentive for capturing CO_2 and injecting it into production fields. An oil producer may be willing to pay for CO_2 because it is a revenue generating input factor. As explained in section 2.1.2, a CO_2 producer will want to capture and store the CO_2 due to quota costs, which forms his commercial incentive. Based on these two incentives it seems interesting to investigate whether a CO_2 value chain, where CO_2 is captured and used for EOR or stored is profitable.

Note that as of today, CO_2 applied for EOR is not subject to quota exemption. A suitable assumption may however be that CO_2 used for EOR is regarded as stored as long as systems for capturing recovered CO_2 from the oil field is in place. The rationale behind such an assumption is that this CO_2 will not be emitted.

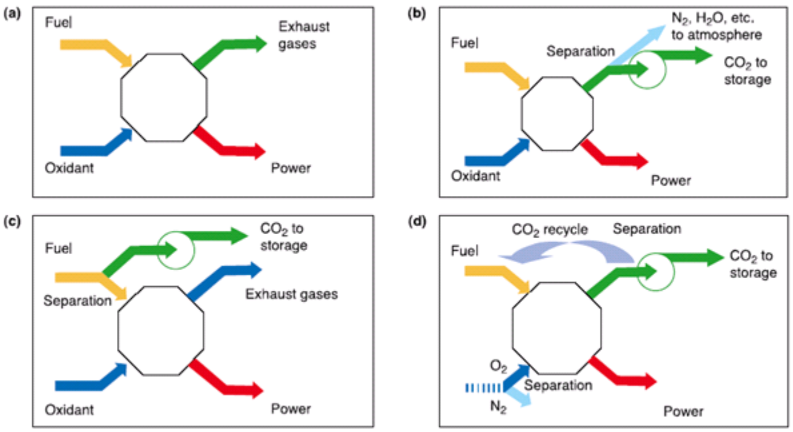
2.3 The technology of a CO_2 value chain

We will introduce the main technological elements of a CO_2 value chain with EOR, where the CO_2 is captured from a gas power plant. CO_2 is captured at the gas power plant, compressed and transported to either an oil field for EOR or an aquifer for storage. The gas power plant is not included in the system. The elements included are capture, EOR, storage and transport.

2.3.1 Capture

Figure 1 illustrates the three methods of capture to be presented and also a case of power production without CO_2 capture. Currently the most common method of capturing CO_2 is *post-combustion decarbonation*, which means cleansing the exhaust gas after combustion. CO_2 is absorbed in a chemical resolution, usually an amine. If a hydrogen rich fuel is used, capture may also take place before combustion. This is called *pre-combustion decarbonation*. This method requires considerable investments on old plants, but might be considered when building new ones. A third way of capturing CO_2 is the *oxyfuel combustion method*, which implies combustion with pure oxygen instead of air. Recycling of CO_2 or water is necessary to moderate the combustion temperature. This process requires the use of new, up to date turbines. (NPD 2005)

Extensive research is currently going on regarding capture technology, and results are exptected to occur shortly.



(a) fossil-fuel-based power generation, (b)post-combustion, (c)pre-combustion, (d)oxyfuel

Figure 1: *Capture techniques (NPD 2005)*

2.3.2 EOR

EOR is an optional element in a CO_2 value chain. If the revenues from the extra oil recovered are higher than the CO_2 purchase cost, investment and operation cost of CO_2 injection, the oil producer may want to purchase CO_2 and inject it. A corresponding logic applies for gas fields, referred to as enhanced gas recovery (EGR). EOR requires modifications at the on- or off-shore oil production installation. Quite often production wells may be recompleted, i.e. be adapted for CO_2 injection instead of oil production (Torp 2008).

The distance between the injection and production wells influences the contact area for CO_2, and it is favorable that it be rather small. At the Norwegian continental shelf this distance is large compared to for instance oil recovery onshore in the US, making it less profitable to implement EOR with CO_2 in Norway. (NPD 2005)

When applying CO_2 for EOR, parts of CO_2 will be reproduced. That is why EOR, as explained in section 2.2, generally is not considered as a method for storage.

Due to the fact that EOR time window is quite narrow, the timing cannot be adapted according to CO_2 supply. The CO_2 demand for EOR will often last for shorter time than the process which produces CO_2. This requires solutions where CO_2may be applied for several purposes or stored.

The technology which is applied for EOR with CO_2 will be based on well known injection technology. The specific application on CO_2 has been in use in for instance the U.S. for a long time. There is however less experience with off-shore implementation.

2.3.3 Storage

If not applied in industrial processes, the captured CO_2 must be stored. Some storage methods are shown in Figure 2. The storage possibilities include geological storage, ocean storage and storage in mineral carbonates (the latter is not illustrated in the figure). Geological storage may be in depleted oil and gas fields, unminable coal beds and deep saline formations on- or off-shore, the latter option also referred to as aquifers. Ocean storage include storage on the seabed or direct release of CO_2 into the water column. (IPCC 2005)

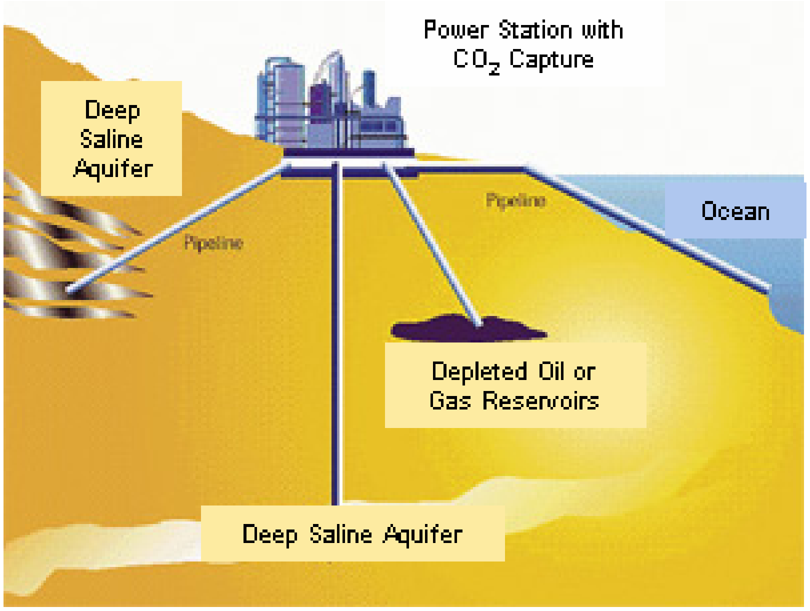


Figure 2: *Storage methods (www.pesa.com.au)*

In Norway the most established method is the one of storing CO_2 in off-shore aquifers. It may also be combined with EOR. The use of CO_2 for EOR is often needed over a short time horizon, and it might be that it does not necessarily correspond with the operation period of the power plant, or opposite. Intermediate storage will be of importance, such as using CO_2 tanks or mountain storage. (NVE 2005)

Future leakage uncertainty

When implementing a CO_2 value chain, it is essential that there exist possibilities for final storage of CO_2. The long term effects of CO_2 storage are not yet mapped and uncertainty is thus an issue. Leakage into the atmosphere is a potential danger in the long term, and this is especially valid for ocean storage. Experiences concerning geological storage have so far not proved to cause leakage. It is nevertheless impossible to prove that such leaks will never appear. Due to the uncertainty related to storage, the public acceptance must be dealt with. Large scale storage will be hard to carry out if public acceptance is poor and policy makers do not have enough information or incentives to support it. (NVE 2005)

International guidelines

When implementing CO_2 storage, there is a number of treaties ratified by the authorities which are to be followed. Regarding off-shore geological storage, there are in particular two conventions that are valid. These are The 1992 OSPAR Convention[4] which is *"the current instrument guiding international co-operation on protection of the marine environment of the North-East Atlantic,"* and Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 and 1996 Protocol Thereto (The London Convention) (NVE 2005). As of today the London Convention prohibits transnational transport of CO_2 for geological offshore storage. Within EU, this issue is however subject to modifications in the proposed EU directive on the geological storage of carbon dioxide from January 2008 which aims to open for transnational transport and geological storage within the EU member states.

There is uncertainty related to future storage regulations, which is not negligible. Recently it seems that the regulations are loosening up when it comes to CO_2 storage (Torp 2008). It is, however, necessary to decide who is to monitor the stored CO_2 in the long term and who is to take on the legal responsibility related to monitoring, potential leakage and other hazards. A common assumption is that authorities will carry the long-term risk.

2.3.4 Transportation

Transportation of CO_2 should be safe and efficient. It is possible to transport CO_2 in solid, liquid or gas phase. Bulk cargo on road, train or ship are options, besides pipelines. For larger volumes ship and pipeline transport are the best candidates. If distances are acceptably short, pipelines are preferred.

Pipeline transport requires a considerate pressure, decided by the pressure level at the end of the pipe, i.e in the storage formation or in the oil reservoir. The temperature may be close to that of the environment. Shipping of CO_2 requires low temperature and a pressure such that the CO_2 is in the liquid phase. Under this condition the CO_2 has a high density, enabling compact packing and thereby less costly ships. Even though ship transport requires a lower pressure than for pipelines, the compression process needed for transforming gas to liquid

---

[4] www.ospar.org

is energy intensive and generates high costs.(NVE 2005)

It is important both for ship and pipeline transport that the CO_2 do not contain too much water, for the issue of corrosion, freezing, and hydrates. In addition, contents of sulfur should be avoided.

Technology for both pipelines and ships are transferable from other similar commodities and will not require considerable research and development. Pipeline CO_2 transport is already taking place in for example the US.

Flexibility in the value chain

In a value chain for CO_2 it is useful to introduce a certain degree of flexibility as the different installations have varying needs and operation time windows, and in order to handle unexpected occurrences.

Ship transport is not a continuous process and will require more embedded flexibility in the value chain than pipeline transport. Intermediate storage capacity is needed at the CO_2 source. The final storage site must have either storage possibility or the ability to receive vast amounts CO_2 in short time.

Whereas pipelines transportation has the advantage of continuous delivery, ship transportation is more flexible as it enables constantly redesign of the value chain. CO_2 may be picked up and delivered at different places, and the quantity transported can also be changed. (NVE 2005)

Safety concerning CO_2 in transport

Safety is an important concern when planning CO_2 transport infrastructure in areas where people live. CO_2 is heavier than air, and might imply particular danger because of its ability to sink into hollows in the landscape, ship hull, basements etc. and stay there without peoples awareness. Safety systems will be needed concerning detection, doubling of valves etc. Transport of CO_2 does not involve the danger of fire or explosion. (NVE 2005)

2.4 Previous work

Several Norwegian institutions have implemented studies examining possible CO_2 value chains and their profitability. Many of which come to the conclusion that such a chain is not profitable. Problem areas frequently mentioned are:

- Sources of CO_2 in Norway are scarce
- EOR requires constant deliveries of CO_2 over a short time period
- The establishment of capture requires CO_2 demand for the entire lifetime of the capture plant

- Risk distribution in the value chain is a problematic issue

The studies apply different oil prices, CO_2 prices, exchange rates, and other conditions and assumptions. Besides, different business models are employed. It is thereby hard to compare and draw an overall conclusion. The net present value (NPV) method is utilized to a large extent.

NPD: ***CO_2 for improved oil recovery on the Norwegian continental shelf - feasibility study***

In 2005 The Norwegian Petroleum Directorate (NPD) carried out a study on the possibilities for a CO_2 value chain, considering also EOR (NPD 2005). The NPD report stressed that import of CO_2 was necessary to cover the need when using it for EOR. The profitability of using CO_2 for EOR was considered by analysing the balance price of CO_2. This method is one of many tools for investment decision making, see section 5.1. The report showed that the costs of establishing a CO_2 chain heavily exceed the income from EOR. Other methods for extracting more oil seemed to be more profitable. The report pointed to the fact that what contributes in making a CO_2 chain unfavorable is that the initial investments are considerable, whereas the income is spread out over several years which occur late in the time horizon, making the present value look rather modest and the risk too high. The resulting balance price is lower than the one companies involved have set as a requirement for their projects.

Bellona: ***CO_2 for EOR on the Norwegian shelf – A case study***

The environment protecting organization Bellona disagreed with the report made by NPD, and created an own report in 2005 (Bellona 2005). Bellona emphasized that an evaluation of a CO_2 value chain should be done in an environmental and socio-economic perspective, and it criticized NPD's use of strongly conservative values. In Bellona's own report they pointed to considerable profits regarding the establishment of a CO_2 value chain in Norway. Bellona's suggestions included that public companies should be in charge of capture and transportation/distribution. In this way the government would take the risk and also obtainthe large profits. Bellona's way of calculating profitability was the NPV method, but they applied a lower discount rate than NPD.

NVE: ***Gas power with CO_2 handling - Value chain evaluations***[5]

The Norwegian Water Resources and Energy Administration (NVE) examined in its report from 2005 the possibilities for CO_2 capture at future gas power plants at Mongstad and Tjeldbergodden with EOR at Gullfaks and Ekofisk (NVE 2005). The conclusion, based on the NPV method, was that none of the cases were profitable, given the current regulating framework in the European energy sector and given the companies' oil price forecasts.

---

[5] Translated from Norwegian title: *Gasskraft med CO_2-håndtering - Verdikjedevurderinger.*

Gassco: *Preliminary negotiations between the commercial actors of a CO_2 chain*[6]

In 2006 Gassco published a report, demanded by the NPD, based on initial negotiations between the actors of a possible CO_2 value chain (Gassco et al. 2006). Like the previously mentioned studies, excluding Bellona, this report explained that a CO_2 value chain is technically, but not economically, feasible. None of the twelve value chains presented had positive net present value. A concept used was the *willingness*, on the behalf of the oil fields, *to pay for* CO_2, which was defined by the EOR income minus the investment and operation costs on the fields.

Shell and StatoilHydro - A feasibility study on the Halten chain

The purpose of this study performed in 2006 and 2007 was to evaluate a value chain in Mid-Norway and Haltenbanken[7]. The concept was a gas power plant with CO_2 capture on Tjeldbergodden and use of the CO_2 for EOR first on Draugen and then on Heidrun. Parts of the generated power was intended to provide the platforms on Draugen and Heidrun with electricity. In June 2007 Shell announced that CO_2 for EOR on Draugen would be too expensive compared to expected increased oil recovery. It was concluded that the value chain was technically feasible, but not commercially viable. Further work is now being done by StatoilHydro to evaluate the possibility for CO_2 for EOR on Heidrun.

2.4.1 Areas for further study

The NPV method is weak in the sense that there is no flexibility in the choice of investment year. Previous studies do not take *timing* flexibility with respect to evaluating the different investment moments for the elements of the value chain, into account. Due to distribution of costs and revenues, and the results of research and development, it might be interesting to investigate how the profitability is affected by this investment flexibility.

Furthermore, deterministic price parameters are applied in all studies. The stochastic nature of prices might in reality play a large role. Since the carbon and crude oil prices are considered to be fundamental drivers of the profitability of a CO_2 value chain, there is a need for a decision making tool which looks at different previews of the future, and which includes the uncertainty of the future prices. So far, the optimal investment timing of the CO_2 value chain activities are not analyzed in a setting of stochastic prices.

---

[6] Translated from Norwegian title: *Innledende forhandlinger mellom de kommersielle aktørene i en CO_2-kjede*

[7] www.shell.com, April 2008

3 Uncertainties in CO_2 value chains

In this section we will qualitatively discuss the most relevant uncertainty factors of CO_2 value chains. These factors should be interesting for decision-makers to be aware of when considering implementation of such chains. When evaluating investment decisions in a value chain, it is not sufficient to consider the deterministic profitability. The uncertainty should also be given attention as thoroughly as possible in the decision basis. The better the decision-makers know the uncertainty, the better prepared they are to make the right decisions. A project which due to calculations of expected net present value (NPV) looks promising, may seem less attractive when the nature of the uncertainty is analysed.

The uncertainties we regard as the most important to analyse are hereby given (they are not necessarily integrated in our value chain model):

- Crude oil prices have proved to be greatly unpredictable. This adds uncertainty to the income potential for a CO_2 value chain with EOR. The crude oil prices also affect the lifetime of an oil field (generally a field is closed when the income does not longer cover the costs of operating it) (NVE 2005).

- The future development of the carbon price is highly important for the profitability of a CO_2 value chain. Because emissions of CO_2 have been priced only for a few years, historical data is not enough to forecast the development of carbon prices. The carbon price will change with government policies, meaning that uncertainties in future policies will lead to uncertainty in the price development. Norway has to decide on how it will handle its commitments concerning quotas in the future, and this choice will influence the economical conditions for, among others, natural gas power plants.

- Natural gas prices represent an uncertainty because EOR may affect the amount of natural gas sold from a field. When EOR is implemented the natural gas may contain a CO_2 level which disqualifies it for sales unless a separation process is included. In decision-making for value chains with EOR with CO_2 a choice between loss of gas sales or cost of separation should be considered. For CO_2 value chains connected to gas power plants the gas price may influence the foundation of the value chain. Additionally, some of the operating costs of the value chains do to a large extent depend on gas prices.

- The energy market in general affects the value chain in several ways. Its uncertainteis may therefore affect the chain as well. Change in price of some energy source may cause a switch in sources. As carbon capture is considered for power plants fired on fossil fuels, the supply of CO_2 will change if the demand for such energy change. Prices, supply and demand of crude oil, natural gas, electricity and carbon emission quotas affect each other mutually, where the correlation is clearest between respectively crude oil and natural gas on one hand, and electricity and emission quotas on the other (NVE 2005).

- Regulatory and political conditions such as taxes, laws, subsidies and international and national regulations contain future uncertainty which are difficult to predict. The issue of obtaining a geological carbon storage permission is an example.
- Public acceptance is of importance for achieving the support of policy-makers. This introduces uncertainty related to storage. It has turned out to be a challenge to convince the general public that injecting CO_2 under ground is acceptable. It is hard to predict if CO_2 storage will in the future be an accepted solution for mitigating climate change. This development may alter the regulating framework for CO_2 value chains.
- Material and labour prices are crucial in investment decisions, and contribute to a large part of the investment cost. Uncertainty in such costs are present in most investment decisions. Over the last years material and labour costs have increased significantly, causing a large rise in costs.
- A possible cost reduction of technology is an area of uncertainty. Continuous research and more experience would speak for a decrease in future costs, but it is anyhow difficult to quantify the effect. In the field of CO_2 capture technology, great effort is presently put into finding the best technology. A possible decrease in costs can be related to reduced component investment costs, simpler construction shape, more effective absorbents and increased energy efficiency (NVE 2005). (Within this aspect the change of material prices is not accounted for).
- Lack of experience with large scale carbon capture at gas power plants enlarges the unpredictability of such projects. Low scale pilot projects are presently projected or carried out. Some of this uncertainty may be resolved in the close future when results from such pilot projects are known.
- Alternatives to CO_2 for EOR may replace a demand for CO_2 in the future, causing the demand for CO_2 to be uncertain.
- The exchange rate risk is crucial for CO_2 value chains. In a Norwegian case, the exchange rates between NOK and respectively USD and EUR are important. The exchange rates are highly volatile.

Uncertainty may be divided into two groups; those which will be resolved independently of the project and those which only will be resolved during or after the project (Dixit and Pindyck, 1994). The uncertainties above belong to the first group. For instance will the carbon price at a specific point in time be realized whether a CO_2 value chain project is undertaken or not. The uncertainties below belong to the second group. For instance does leakage from the storage site represent an uncertainty which only will be known if a specific carbon storage project is undertaken. In projects which are of such a new nature as CO_2 value chains with EOR, the first projects will suffer from lack of experience, which again later projects may benefit from.

- The CO_2 supply for EOR is uncertain due to down time of the installation supplying CO_2-rich gas to the capture plant, as well as down time for the capture plant itself. The CO_2 supply is also uncertain with regards to the life time of the gas power plant (or other supplier).
- Reservoir technical uncertainty may occur at both EOR site and storage site. For instance may geological or seismical conditions differ from what was expected. The exact amount of CO_2 required for EOR is uncertain. The amount of extra oil which may be recovered by EOR, is an uncertainty which directly affects the revenue potential.Due to the specific (unknown) characteristics of each reservoir, such uncertainties will not be resolved before the project is actually implemented.
- Intermediate and permanent storage capacity may differ from what was expected and cause flow or accumulations problems.
- Costs occurring when implementing EOR are uncertain due to several field specific factors which for instance influence the required number of wells and whether new wells are required or production wells may be refitted. Modifications of equipment at the production installation may be necessary (e.g. to prevent corrosion due to H_2O and CO_2) and represent another uncertain cost.
- The impacts of the injected CO_2 on the products from the field (oil and/or natural gas) are regarded as uncertainties and may for example cause reduced natural gas sales due to increased CO_2-content in the gas.
- The exact shut-down of the field is uncertain and thereby the demanded amount of CO_2 for EOR.
- Whether CO_2 in the distant future will leak from the storage site is uncertain. The consequences of such leakage are hard to map completely. This area is presently subject to extensive research and is dedicated much attention in the IPCC Fourth Assessment Report (IPCC 2005).

Uncertainty implementation in decision-making

Uncertainty may be implemented in decision-making by means of stochastic approaches which allow for the distribution for the uncertain parameter to vary over time. Parameters of high influence on the results should be modeled stochastically. Sensitivity analysis is a measure for considering the impact of deviations from applied values of specific parameters on the result. It is important to be aware of that sensitivity analysis is not an alternative for analysing decision making under uncertainty. Wallace in (Wallace 2000) argues that sensitivity analysis only is appropriate for variations in deterministic parameters, or in uncertain parameters when predicting what a decision in the future will be when we will make decisions under *certainty*.

4 The simplified CO_2 value chain of Tjeldbergodden and Heidrun with optional EOR

In this section we carefully go through the particular value chain of this thesis. We describe the physical elements throughout the chain to the extent we mean is appropriate for understanding the model and the results. We state the assumptions and simplifications on which the system is based. Where it is applicable we explain why such assumptions are included. Assumptions are made when, considering the purpose of the analysis, the real case is more complex or uncertain than what is appropriate for the given decision context, or when due to confidentiality actual facts about the value chain may not be given. Where other information is not provided, assumptions for the value chain are given by Tore Torp, StatoilHydro through meetings, e-mails and telephone contact during spring 2008.

In this thesis a CO_2 value chain is modelled with the goal of maximizing the overall profit without respect to the different actors. Hence, transaction costs between actors, such as CO_2 purchase costs, are disregarded. This way of optimizing the value chain will lead to the deduction of its maximal financial potential that society may benefit from. Generally, value is added throughout the chain if the net present value (NPV) of the cash flow should turn out positive. Investing in projects which reduces the magnitude of a negative NPV may also be regarded as value-adding. Figure 3 illustrates a CO_2 value chain and its activities; CO_2 sources where the CO_2 is produced, the ways of CO_2 transportation and the sinks to which CO_2 is delivered.

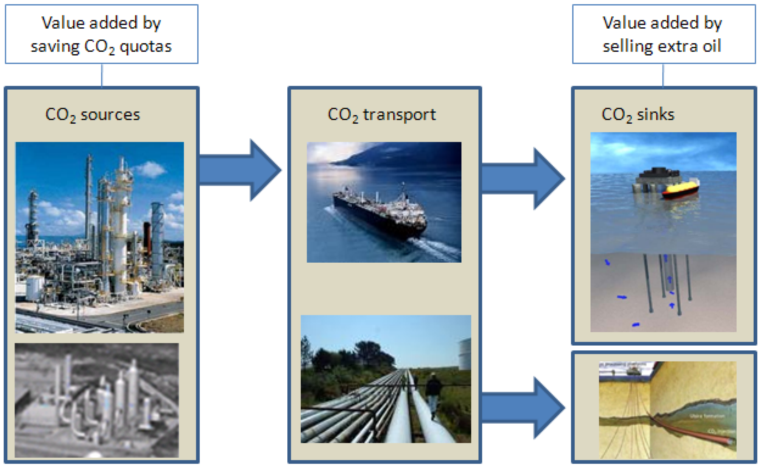


Figure 3: *The value chain of CO_2*

In the previous section a large range of uncertainties which may occur in CO_2 value chains were outlined. Some of these uncertainties will in this section be dealt with by assumptions, which within this thesis resolve the uncertainty. The two uncertainties which are considered the most important in this thesis, are those of the crude oil price and the carbon emission quota price. This is because the two main incentives for the value chain, described in section 2, are heavily reliant on the carbon and oil price. The oil sales represent the only revenues obtainable, whereas the carbon emission quotas constitute the opportunity cost. The fact that the focus of this thesis is economical rather that technical also influences the choice of parameters to be imposed a stochastic approach. The way the stochastic approach is carried out is described in section 5. In section 6 we show the results of the sensitivity analysis for a selection of other parameters.

4.1 The real case: Tjeldbergodden gas power plant and Heidrun production field

A gas power plant has been planned at Tjeldbergodden for a long time. The process is frozen until the carbon emission situations is clarified with regards to emission permission or capture plant. An account of this situation along with the main principles of the gas power plant is given in Appendix A. As of today methanol production is the main activity at Tjeldbergodden. Tjeldbergodden receives natural gas from the Heidrun field through the 250 km long Haltenpipe which is operated by Gassco. This gas is exclusively employed for local methanol production. The gas power plant is not inside the value chain interface in this thesis, which regards a system consisting of a carbon captur plant, EOR facilities, storage facilities and pipelines. The value chain is based on Tjeldbergodden and the Heidrun field, but is simplified to such an extent that it does not represent the real case.

The Heidrun field is a production field where oil represents the main production, even though natural gas also is produced. Figure 4 shows a picture of the production platform. The fact that Heidrun approaches its last production phase - a phase in which EOR with CO_2 may be beneficial - simultaneously as there may be CO_2 supply from Tjeldbergodden, opens for the possibility of creating a value chain. In addition, there exists an aquifer 80 km away from Heidrun which may serve as a permanent storage site for CO_2. This formation is referred to as the Alpha structure.

Figure 4: The Heidrun platform

4.2 The simplified value chain design

In this thesis we suppose that *the gas power plant is already built* and that *power production without capture is ongoing*. Furthermore, we suppose that carbon emission quotas is the only measure policy makers control for reducing emissions, so that *carbon emission quotas must be bought for produced CO_2 which is not captured.* The power plant has accordingly a choice between: i) to emit produced CO_2 and buy carbon emission quotas, or ii) to invest in facilities for capturing and storing produced CO_2.

Option i) represents the cost of doing nothing. This cost corresponds to the cost of purchasing carbon emission quotas for the amount of CO_2 which would have been captured if capture plant was running. As the purpose of this thesis is to consider investment timing of a possible CO_2 value chain, the moment when leaving regime i) and entering regime ii) is of crucial interest within this work.

Option ii) implies investment in capture and storage facilities. These facilities will consist of:

- CO_2 capture plant at Tjeldbergodden gas power plant
- CO_2 injection well at the Alpha structure
- CO_2 pipelines between Tjeldbergodden and Heidrun, and between Heidrun and the Alpha structure.
- Optional: CO_2 injection well with required process equipment at the Heidrun field and platform.

A sketched map of the value chain is shown in figure 5. In the following the physical elements of the chain listed above, will be described.

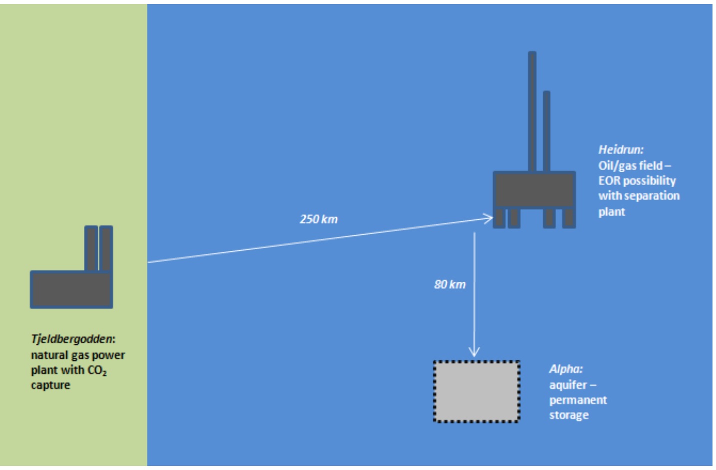


Figure 5: *The value chain*

4.2.1 Capture plant

The capture technology which is considered in this analysis is post-combustion, refer to section 2.3. The rationale behind this assumption is that the two other capture approaches pre-combustion and oxy-fuel are not expected to be mature enough to be considered within the relevant time frame of this value chain. Large Nordic producers of energy from fossil fuel, including StatoilHydro, tend towards preferring post-combustion technology at the time being.

We assume that when capture technology is in place, 2 Mtonnes of CO_2 *will be captured every year as long as the gas power plant is producing. The power plant is assumed to have a lifetime of 25 years.* The supply of CO_2 is thus available through the time horizon of 23 years applied in this thesis (2008-2030).

If capture technology is implemented, a compressor is included at Tjeldbergodden in order to give the CO_2 a pressure of 200 bar. This implies that no further compression is necessary at Heidrun before injecting the CO_2 (Røkke 2008). Within our value chain model, facilitating for storage at the Alpha structure and pipeline transport must also be done when capture is implemented. We will come back to the reason behind this in section 4.2.3 which deals with storage.

4.2.2 EOR and separation facilities

The implementation of EOR with CO_2 at Heidrun is optional if capture at Tjeldbergodden is implemented. The incentive for implementing EOR with CO_2 is discussed in section 2.2.1. *If EOR with* CO_2 *is implemented at Heidrun, the gross yearly* CO_2 *demand will be 2 Mtonnes.*

If it is decided that EOR is to be included, a CO_2 injection well is needed at the Heidrun field. The process of fitting a production well into an injection well is referred to as recompletion. In a financial perspective this method is highly preferable as compared to drilling a new well. However, it is only possible if there already is a production well at the location where the CO_2-injection well should be located. At the Heidrun field 51 production wells are drilled or projected[8]. *In this analysis we assume that there exists a production well which is located at a suitable CO_2 injection location. It is assumed that one injection well is sufficient at the Heidrun field.* This assumption is based on experience from Sleipner where the geological conditions are comparable to those at Heidrun.

When EOR is implemented, some of the injected CO_2 will be recovered with natural gas. After a certain period of time, this will cause the CO_2 content of the natural gas to exceed the accepted level and the gas may not be used at Tjeldbergodden (or sold to other actors). There are two ways of dealing with this issue. A separation module may be included at Heidrun, in which CO_2 will be separated from natural gas, in order to let CO_2 be re-injected in the field for EOR and natural gas be employed commercially. The separation technology is based on similar technology as that of the capture plant. The other option is to re-inject the CO_2-rich natural gas. This option implies a loss of gas revenues. In our model the first option is selected. Figure 6 shows the annual[9] CO_2 flows of the system, and they will now be described . *We assume that separation is necessary two years after EOR starts. The CO_2 content of the gas is assumed to be constant and corresponds to 0.8 Mtonnes of CO_2 every year.* As the CO_2 will be re-injected, the net demand for CO_2 to Heidrun decreases. Because the CO_2 flow from Tjeldbergodden is constant, *a slip stream of 0.8 Mtonnes will be led to the Alpha-structure for storage* instead of being employed for EOR.

---

[8] http://www.statoilhydro.com/no/OurOperations/ExplorationProd/ncs/heidrun/Pages/default.aspx

[9] Annual flows from the third year of CO_2 injection, i.e. when CO_2 in reproduced

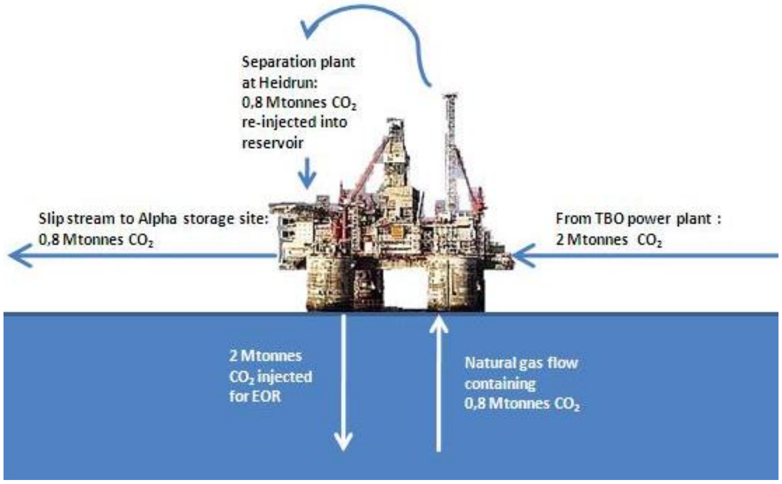


Figure 6: *Annual CO_2 flows after two years of CO_2 injection for EOR*

As the lifetime of the gas power plant is assumed to be 25 years, and the production of Heidrun will continue for 23 years (until 2030), *we assume that CO_2 from Tjeldbergodden will be supplied to Heidrun through all EOR years.*

As mentioned in section 2.2, due to the fact that CO_2 is reproduced after it has been injected for EOR, CO_2 applied for EOR does presently require emission quotas. In this value chain, however, CO_2 used for EOR is not emitted because reproduced EOR will be captured and re-injected. *We assume that CO_2 used for EOR qualifies for emission quota exemption.*

Accurate estimation of the amount of extra oil extractable with CO_2 injection may be carried out by reservoir simulations based on time window, amount of CO_2 injected, geology and other factors. As the production companies rarely want to reveal these values or the required information for performing the simulations, an approximation is provided for this analysis. According to the production company an approximation will be sufficient for this level of details because the total amount of extra oil which may be recovered will not depend greatly on the timing of EOR (when EOR starts and for how many years it lasts). *It is assumed that EOR will increase the total extractable volume by 5 % independent of EOR timing. This extra volume is expected produced by equal annual amounts from the third year of EOR until the field is closed in 2030.* Figure 7 illustrates how the annual volume of extra oil only depends on the duration of EOR. It takes time for the oil to move in the reservoir. Hence, *we assume that there is a delay of two years from CO_2 injection starts until extra oil is recovered.* In this value chain it is not an option to return to normal production after EOR is undertaken. *If EOR is started, it will last until 2030. The CO_2 injection may at the earliest begin in 2015 and at the latest in 2022, implying that extra oil is* *recovered from no earlier than 2017 and no later than 2024.*

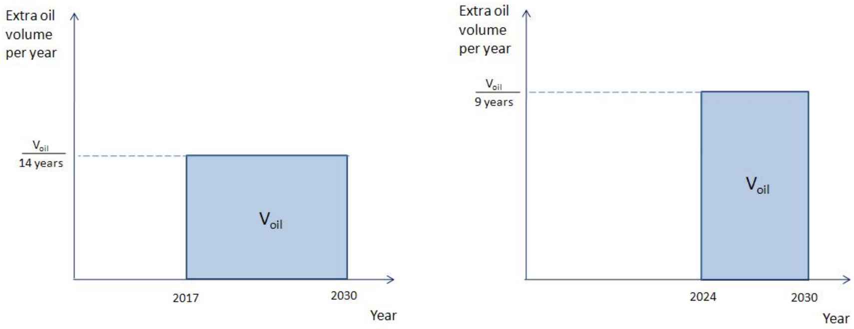


Figure 7: *The annual extra oil volume*

Water and CO_2 will accompany the oil stream up the well. This introduces a challenge, namely the high corrosivity of mixed H_2O and CO_2. An option is to replace all components and pipelines which will be in contact with this flow into components consisting of corrosion resistant materials. Alternatively, the flow must be treated in order to remove H_2O from the CO_2 gas. The latter option is assumed to be the preferred solution, due to the high costs of changing equipment before its lifetime is reached. This is not dealt with in our analysis.

4.2.3 Storage facilities

The Alpha structure is due to its geological properties (off-shore saline formation/aquifer) well suited for permanent geological CO_2 storage. As it is within Norwegian territories it is not affected by the transnational storage prohibition imposed by the London Convention, which was mentioned in section 2.3.3. A storage permission is not yet obtained, but StatoilHydro believes that this will be sorted out. *We disregard costs, time and uncertainty related to obtaining a storage permission at the Alpha structure.*

In order to prepare for CO_2-injection at the Alpha structure, an injection well has to be drilled. Should it turn out that it is optimal to start EOR with CO_2 at Heidrun as soon as captured CO_2 is available, principally the storage capacity at the Alpha structure will not be needed until two years later, when re-injection of recovered CO_2 in Heidrun reduces net CO_2 demand. However, *pipeline and injection well must be in place at the Alpha structure when capture starts.* The rationale behind this assumption is that in case of production stop and thus CO_2 injection stop at Heidrun, there must be a way to handle the CO_2 flow from Tjeldbergodden. By means of a valve mechanism at Heidrun one can control whether the CO_2 flow from Tjeldbergodden is directed to EOR injection at Heidrun or to permanent storage in the Alpha structure.

The gas power plant with a life time of 25 years will continue producing CO_2 after the field shuts down in 2030. It will still be necessary to handle the captured CO_2. *We assume that the capacity of the Alpha structure is large enough for receiving CO_2 from Tjeldbergodden throughout the life time of the gas power plant.*

CO_2 recovery from geological storage

With the assumptions stated earlier in this section of an annual CO_2 supply of two million tonnes from Tjeldbergodden if capture plant is installed, and a gross demand for the same amount of CO_2 for EOR in Heidrun, recovery of CO_2 from the Alpha structure will not be necessary in this value chain. *CO_2 recovery from the storage site is therefore not included in this analysis.*

It should nevertheless be noted that this is a possibility with a recovery rate of approximately 35%. If it should be favorable or necessary at a later point in time to recover the injected CO_2, this cannot be accomplished through the injection well(s).

4.2.4 Pipelines

For the 250 km distance Tjeldbergodden-Heidrun it is just as suitable to apply pipelines as ship transportation, refer to (SINTEF 2005). *We assume that pipelines are the chosen type of CO_2 transportation.* The pipelines are to be installed between Tjeldbergodden and the Heidrun field, and between the Heidrun field and the Alpha structure. *The lifetime of the pipelines are assumed to be longer than that of the gas power plant.*

4.3 Decisions in the value chain

We attempt to suggest the best timing of the investments in the value chain based on the given assumptions. There are two investment decisions which are evaluated. All other investments in the value chain follow implicitly from the two decisions stated below.

The first decision to be taken for this value chain is whether capture technology is to be installed. This decision may be taken immediately or it may be postponed in order for the decision to be taken under conditions where some of the uncertainty related to carbon and crude oil prices are resolved. This decision implicitly controls investment decisions regarding injection well at the Alpha structure and all pipelines, as they will be built if and only if capture is implemented. If it is decided to install capture technology at a specific point of time, a second decision of implementing EOR with CO_2 may be taken. It may be found optimal to invest in EOR immediately, or it may be more profitable to wait. If this investment is postponed, some of the uncertainty related to the oil prices and thereby to the revenue potential in the future is resolved. Postponing the EOR decision implies storage of captured CO_2 in the Alpha structure

4.4 Owners and operators

In this section the owner and the operators of the main components of the value chain are presented. This structure does however not affect the analysis in this thesis because the value chain is regarded as one integrated system without internal barriers, objectives or transactions. The split ownership which in reality must be dealt with, may cause sub-optimality. Each company maximizing their own profit usually causes the overall supply chain profit to decrease. This problem, called "double marginalization", may be overcome by establishing suitable contracts which could contain elements like rules for revenue sharing (Kreps 2004).

StatoilHydro will own and operate the capture plant at Tjeldbergodden if it is installed.

Heidrun production platform is operated by StatoilHydro. The concessionaries are Petoro AS (58.16 %), Norwegian ConocoPhillips AS (24.31 %), StatoilHydro ASA (12.40 %) and Eni Norway (5.12 %) (NPD 2007).

The Alpha structure is not presently employed and is inactively managed by the authorities. StatoilHydro assumes that they will be given permission to introduce geological storage of CO_2 and be responsible of the risk, at least in a short term perspective. As the CO_2 will be stored permanently, the owner of this area will expose himself to an unknown risk in the distant future. In order to reduce risk and thereby encourage CO_2 storage, a solution may be that the government adopts the ownership and thus the responsibility for the substances and the deposit site.

4.5 Review of assumptions and simplifications

In this part we give a summary of the most important assumptions and simplifications so that they are clear to the reader before the mathematical model is described in the next section. Most assumptions regarding costs and other specific input values are given in section 5.4.

Assumptions and simplifications for option without capture

- Carbon emission quotas for two million tonnes of CO_2 must be purchased every year.

Assumptions and simplifications for capture

- Two million tonnes of CO_2 will be captured every year from 2008 and as long as the power plant is running.
- The gas power plant has a life time of 25 years.
- The applied technology is post-combustion capture.

Assumptions and simplifications for EOR with CO_2

- The gross yearly CO_2 demand will be two million tonnes.
- CO_2 from Tjeldbergodden will be supplied to Heidrun through all EOR years.
- There exists a production well at the Heidrun field which is located at a suitable CO_2 injection spot. One CO_2 injection well is sufficient at the Heidrun field.
- Separation of CO_2 and natural gas will be necessary from two years after EOR has started.
- The CO_2 content of the natural gas is constant and corresponds to 0.8 Mtonnes of CO_2 every year. A slip stream of 0.8 Mtonnes will be led to the Alpha-structure for storage every year from two years after EOR is started.
- EOR will increase the total extractable volume of oil with 5% independently of EOR timing. The extra oil is produced with equal amounts every year from the third year or EOR until the field shuts down in 2030.
- The CO_2 injection may at the earliest begin in 2015 and at the latest in 2022, implying that extra oil is recovered from no earlier than 2017 and no later than 2024.

Assumptions and simplifications for storage

- CO_2 injection well must be in place when capture starts.
- CO_2 recovery from storage site is not arranged for.
- The capacity of the Alpha structure is large enough for receiving CO_2 from Tjeldbergodden throughout the life time of the gas power plant.

Assumptions and simplifications for transport

- Pipelines are the chosen type of transportation for CO_2.
- All pipelines must be in place when capture starts.
- The lifetime of the pipelines are higher that that of the gas power plant.

Assumptions and simplifications related to political decisions

- Power production takes place from today at Tjeldbergodden gas power plant.
- CO_2 used for EOR with separation and re-injection qualifies for carbon emission quota exemption.
- Costs, time and uncertainty related to obtaining storage permission at the Alpha structure are disregarded.

5 Description of the mathematical model

The purpose of this section is to present the mathematical model behind the investment analysis that is to be done in this thesis. Firstly, the chosen approach is to be introduced, based on a short discussion of available decision making tools and methods. Some important properties of the main mathematical model is then presented in the context of the case studied, folllowed by how Monte Carlo simulation is implemented. Finally, the input data of the mathematical program is summarised.

5.1 A real options approach

There is a variety of tools available for decision making related to investment projects. According to The Norwegian Petroleum Directorate (NPD)[10] for the petroleum industry the most common decision making tools are the net present value method (NPV), NPV indices (NPV compared to investments) and the internal rate of return method (irr). Additionally, NPD presents the balance price as an applied concept. For oil companies, the balance price typically indicates the average crude oil price over the production period, in order to be economically profitable. When projects are compared, the one obtaining a smaller balance price is the most favorable. Balance price differs from other methods for decision making in the sense that it does not require an exact representation of the parameter in question, such as the crude oil price. This is favorable in the sense that the crude oil price is highly uncertain. Another utilized method of trying to understand the uncertainty is sensitivity analysis.

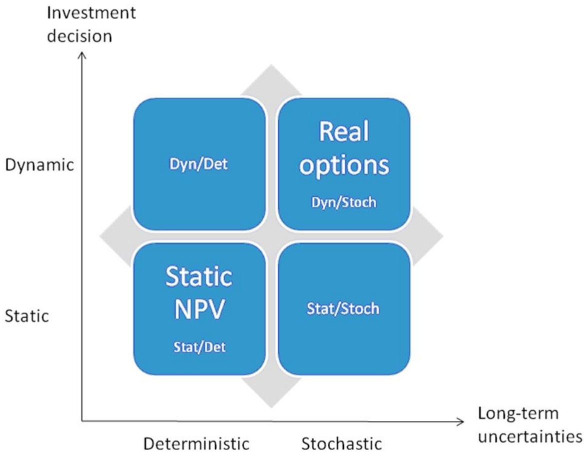


Figure 8: *Comparison of the static NPV method and ROA*

The main purpose of this thesis is to analyse the *timing* decisions of in-

---

[10] www.npd.no (visited April 2008)

vestments in a CO_2 value chain. A real options approach (ROA) is chosen for this purpose. An ROA uses principles from financial option valuation and is an alternative to traditional decision making tools mentioned above. An opportunity to invest can be seen as a real option if the investment decision is irreversible, and there is flexibility concerning the investment timing. Real options theory values the option to invest in the future instead of investing today and emphasizes that the ability to delay can profoundly affect an investment decision. The ROA rule is to accept a project only if the value of the project exceeds the value of keeping the investment option alive. Figure 8 is derived from (Botterud and Korpås 2007) and shows how ROA differs from a static NPV method[11]. In addition to the ability to delay an investment, ROA adds one more aspect compared to a static NPV; it includes uncertainty for factors that affect the investment decisions.

Stochastic-dynamic programming may be applied for real options valuation. Thorough theory about stochastic dynamic programming for real options valuation can be found in (Dixit and Pindyck 1994) and (Kall and Wallace 1994).

The stochastic dynamic programming model made for thesis is modelled in XpressMP. The complete code is available in Appendix G. The most central parts of it are explained more thoroughly in the following sections.

5.2 The stochastic dynamic model

In reality there are in this model two sorts of what is usually referred to as *states*; price states and investment states. A price state gives, through the way it is modelled, a unique combination of a CO_2 and a crude oil price, and from now on we refer to this as a price *node* or price *scenario*. Whenever state is mentioned, it is referred to investment states. A decision is made at each stage, which in the model corresponds to a year. Uncertainty is resolved in time increments of one year as well.

When nothing else is mentioned, all assumptions concerning technology and related costs are made in accordance to conversations with Tore Torp in StatoilHydro.

5.2.1 Handling uncertainties

Crude oil prices and carbon prices are modelled as stochastic processes in our model. Other uncertain elements in the CO_2 value chain are discussed qualitatively in section 3, and some are treated further in sensitivity analysis.

How to model the uncertain development of commodity prices has been widely

---

[11] The static NPV method refers to the NPV method when only one possible investment year is considered. The NPV method may be more dynamic if NPVs for various possible investment years were calculated and compared.

discussed in the literature. Short-term and long-term deviations have different characteristics that affect the price development and thereby the modelling method. Short-term volatility (variations within a time frame that is less than a year) is caused by conditions in the market that may change rapidly, and is often modelled as a mean-reverting process. Long-term volatility is caused by more underlying uncertainties and is often modelled as a random walk process. (Schwartz and Smith 2000) is an example of a paper discussing the short-term variations and long-term dynamics in commodity prices. Schwartz and Smith here present a two factor model where a geometric Brownian motion (random walk) with drift represents the equilibrium price level and reflects the long-term uncertainty, and where an Ornstein-Uhlenbeck process represents the short-term deviations. In the same paper they argue that for long-term investments, it is sufficient to consider only the uncertainty in equilibrium prices, that can be modelled using a standard GBM. Pindyck in (Pindyck 2001) supports this and argues, partly based on studies in (Pindyck 1999), that for real options, which usually have long time horizon, the long-run behavior of prices and volatility is more relevant than short-term deviations. He also suggests that for investment decisions where energy prices are the stochastic variables, using a geometric Brownian motion will only lead to minor errors in an optimal investment rule.

Because this thesis deals with strategic investment decisions with a time frame of 23 years it is, based on the above discussion, assumed that only the long-term uncertainties drive the investment decisions. The short-term volatility is disregarded, and the price developments are modelled as GBMs.

It should still be mentioned that using only a GBM has been criticized. Bernard, Khalaf et.al. in (Bernard and Khalaf 2008) claim that since the convenience yield of oil has a stochastic nature, mean reversion would be more appropriate. Further details are found in the article.

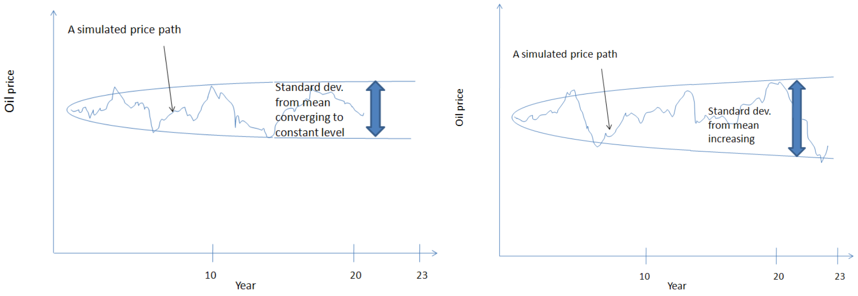
Continuous price modelling

GBM is a stochastic process occurring in continuous time that follows equation 1 given by (McDonald 2006):

$$dP(t)/P(t) = \mu dt + \sigma dZ(t) \tag{1}$$

A GBM is often used to describe a stock price development, as in by (McDonald 2006). In more relevant terms for this thesis the $P(t)$ is the time-dependent price, $dP(t)$ is the instantaneous change in the price, μ is the expected percentage drift and σ is the percentage volatility. $Z(t)$ is a random variable and represents the Brownian motion, also called a Wiener process. Given the current price $P(0)$, $P(t)$ follows a log-normal distribution. The increments to $Z(t)$ are independent and over small periods of time they are normally distributed with a variance that is proportional to the length of the time period (McDonald 2006).

The volatility is given by the annual standard deviation. The annual standard deviation in a GBM is the amount that the expected future prices may drift up or down each year. Even if the volatility for the prices following a GBM process has a constant value, the variance of the distribution of prices grows linearly with time. In other words, a GBM implies that the average distance from the starting point increases with the number of time periods. This characteristic is illustrated for oil prices in the right graph in Figure 9. As a comparison the development of a mean reverting process is given in the left graph. For the mean reverting process, the variance of the distribution of prices converges to a constant level, and the long-term prediction is associated with the long run mean parameter.



(a) Mean reversion (b) Brownian motion

Figure 9: *Comparison of long term developments in prices*

Discrete price modelling

A normal approach to making a GBM discrete is representation in a binomial tree. A binomial tree is a scenario tree where the development of the uncertain parameter is modelled as discrete at given points in time. Each node in a tree is related to one price state in one specific point in time. The movements in a binomial tree are represented by “up” and “down” movements and the probability p of an up movement. Figure 10 gives a graphical illustration of a binomial tree. Because all the paths leading to each of the nodes contain the same number of up moves and the same number of down moves (in different orders), this tree is called a recombining tree. Recombining trees are more tractable than non-recombining trees because the number of nodes are far fewer. The parameters for the “up” and “down” movements and the probability must give the right values for the expected value and variance of the price change during each time period (Hull 2006, p.392). When the prices follow a log-normal distribution, which is the case for GBM, the node values (prices) can be set by the ”up” and ”down” equations 2 and 3, introduced by Cox, Ross and Rubinstein in 1979 (Hull 2006).

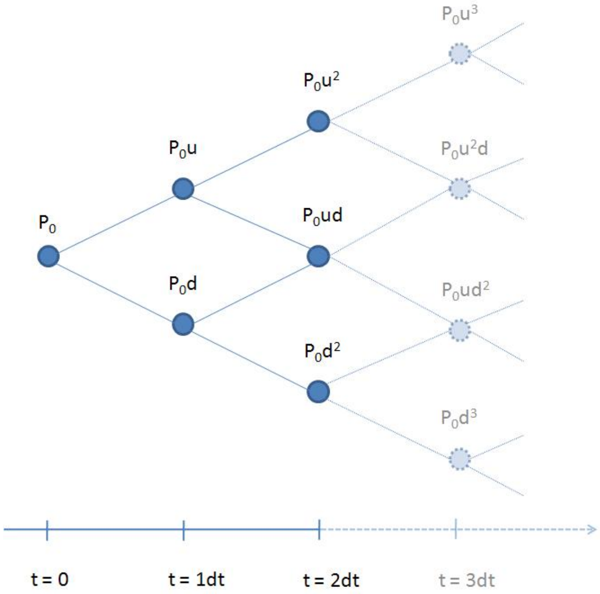


Figure 10: *Recombining binomial tree*

$$u = e^{\sigma\sqrt{dt}} \tag{2}$$

$$d = \frac{1}{u} \tag{3}$$

By constructing the tree using the Cox, Ross and Rubinstein method, if the volatility is constant throughout the time horizon, the tree will be recombining. The probability of moving from one node to another is given by equation 4 (Hull 2006):

$$p = \frac{(e^{\mu dt} - d)}{(u - d)} \tag{4}$$

Constructing trees by using these formulas has one drawback that is mentioned by (Hull 2006). The probability p becomes negative if the time-periods are long or the drift between two consecutive time-periods is high, and $\sigma < |\mu\sqrt{dt}|$.

There are ways to construct the tree with no negative probabilities. (Hull 2006) suggests that in stead of imposing $d = 1/u$. p can be set to 0.5. The corresponding equations for "up" and "down" are given in equations 5 and 6.

$$u = e^{(\mu-\sigma^2/2)dt+\sqrt{dt}} \tag{5}$$

$$d = e^{(\mu-\sigma^2/2)dt-\sqrt{dt}} \tag{6}$$

In this thesis both the crude oil price and the CO_2 price are to be modelled as stochastic processes. Because these prices are correlated, refer to section 5.4.5, modelling the two prices in two independent binomial trees will give an incorrect representation of the movements in prices. The prices are therefore modelled using one common non-rectangular tree as described in (Rubinstein 1995). It is a recombining three dimensional tree where one node in the tree represents one crude oil and one CO_2 price in a time period. The probability of moving from one price node to each of the possible succeeding nodes is 0.25. There will always be four succeeding nodes from one node. If the prices of commodity 1 and 2 are given by $P1_{n1}$and $P2_{n1}$ in node 1, and the correlation factor is ρ, the values of the succeeding nodes are given in equations 7 - 10 (derived from (Hull 2006, p.578)).

$$Node\,2:\ P1_{n2} = P1_{n1}u\ ,\ P2_{n2} = P2_{n1}A \tag{7}$$

$$Node\,3:\ P1_{n3} = P1_{n1}u\ ,\ P2_{n3} = P2_{n1}B \tag{8}$$

$$Node\,4:\ P1_{n4} = P1_{n1}d\ ,\ P2_{n4} = P2_{n1}C \tag{9}$$

$$Node\,5:\ P1_{n5} = P1_{n1}d\ ,\ P2_{n5} = P2_{n1}D \tag{10}$$

where

$$u = e^{(\mu_1-\sigma_1^2/2)dt+\sigma_1\sqrt{dt}} \tag{11}$$

$$d = e^{(\mu_1-\sigma_1^2/2)dt-\sigma_1\sqrt{dt}} \tag{12}$$

$$A = e^{(\mu_2-\sigma_2^2/2)dt+\sigma_2\sqrt{dt}(\rho+\sqrt{1-\rho^2})} \tag{13}$$

$$B = e^{(\mu_2-\sigma_2^2/2)dt+\sigma_2\sqrt{dt}(\rho-\sqrt{1-\rho^2})} \tag{14}$$

$$C = e^{(\mu_2-\sigma_2^2/2)dt-\sigma_2\sqrt{dt}(\rho-\sqrt{1-\rho^2})} \tag{15}$$

$$D = e^{(\mu_2-\sigma_2^2/2)dt-\sigma_2\sqrt{dt}(\rho+\sqrt{1-\rho^2})} \tag{16}$$

The non-rectangular tree for the possible price combinations for two commodities, may be be visualized as a "binomial pyramid" where there is one layer of nodes consisting of p^2 nodes for each period p. For the first commodity the price may move up or down, multiplying the present price with u or d with equal probabilities. If the first commodity moves up, the price of the second may move with a factor corresponding to A or B with equal probabilities. If the first commodity price moves down, the price of the second may move with a factor corresponding to C or D with equal probabilities. For the tree to recombine, constant drift parameters and volatilities must be used for the whole time horizon, so that $AD = BC$ (Hull 2006).For the purpose of illustrating recombinations, the nodes of the second move, i.e from period 2 to period 3, are illustrated in Figure 11. From any node in period 2 (marked as crosses in the figure), the four surrounding nodes in period 3 (dots in the figure) may each be reached with a probability of 0.25. Each node is labeled with the factors that are to be multiplied with the initial prices for the two commodities, and the products will be the prices in that node. Any node in period 3 which is not a corner-node, may be reached from several nodes in period 2. For instance may node (u^2, AB) be reached by going from either (u, A) or (u, B).

The prices in the different nodes in the non-rectangular tree are calculated within the model. The XpressMP code for this calculation is included in the code for the full model in G.

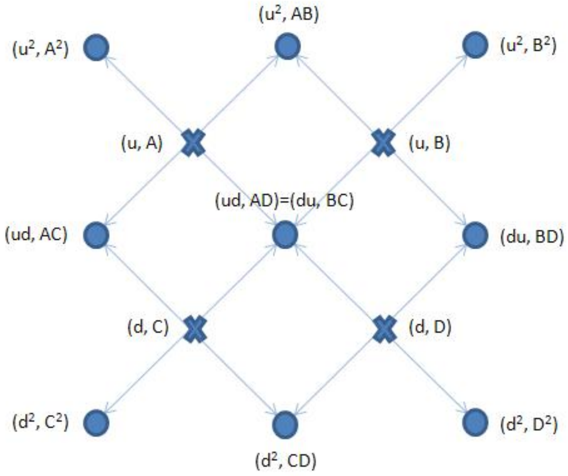


Figure 11: *The second move in a recombining tree*

5.2.2 Investment states

The various states of our model will here be listed. Power production in the gas power plant is assumed to be present in all states.

1. No investments
2. Invest in capture plant part 1
3. Invest in capture plant part 2
4. Invest in capture plant part 3, all pipelines and injection well at Alpha
5. Invest in capture plant part 3, all pipelines, injection well at Alpha, separation unit at Heidrun part 1 and preparation for EOR at Heidrun

6. Operation of capture, pipelines and injection well at Alpha
7. Operation of capture, pipelines and injection well at Alpha. Invest in separation unit at Heidrun part 1 and preparation for EOR at Heidrun
8. Operation of capture, pipelines and EOR Heidrun first year. Invest in separation unit at Heidrun part 2
9. Operation of capture, pipelines and EOR Heidrun second year. Invest in separation unit at Heidrun part 3
10. Operation of capture, pipelines, injetion well at Alpha, separation unit and EOR Heidrun further years

The opening decision is on whether to invest in capture or not. If it is chosen to do nothing, the system stays in state 1. It is possible to stay here until the end of the time horizon, or move to state 2 at any time. Choosing to invest leads into an investment process consisting of three parts, implying the cash flows representing different percentages of the total investment amount. This process is further described in section 5.4. The lead time of building a capture plant is assumed to be three years - meaning that operation takes place in the fourth year.

The decision on building the pipeline system is in the model connected to building the capture plant. The lead time on pipelines is set to one year. This implies that as soon as the capture investment process is started, the investment cost of the pipelines occurs in year three of the capture investment process, so that the operation of pipelines and capture are initiated in the same year. The same holds for the injection well at Alpha. It is assumed that if capture is chosen, a pipeline system as well as a storage are also implemented.

The next choice is that on EOR. A separation unit at Heidrun is in our model inseparable from EOR implementation, because we have assumed that this is how we handle the CO_2 rich natural gas produced under EOR. The lead time of building such a separation unit is also three years, equal to that of the capture installation, which is the same technology. Such a unit is necessary as late as in the third year of EOR operation, because this is when the produced gas becomes polluted with CO_2. The investment thus has to be started three years before this point, and may be initiated already while investing in capture (state 5) or while operating storage (state 7). This process coincides with the investment in EOR (recompletion), which has a lead time of one year. Summing up, the decision of EOR implies the initiating of separation unit and recompletion investment processes. Additionally, it is assumed that it takes two years from the CO_2 is injected in the oil field, until additional oil is extracted (state 10). This delays the income from EOR with two years after operation start.

State transitions and time restrictions

Figure 12 illustrates the possible state transitions in a state diagram. Because some of the state transitions only may occur in specified time windows, the diagram includes the time dimension. The restrictions are imposed because of the time window within which EOR may be initiated. The earliest start for EOR is in 2015. This means that it is not allowed to enter any state implying operation of EOR, before this time period. EOR must be terminated in year 2030.

A table describing the states and the arising costs and revenues is given in Appendix B.

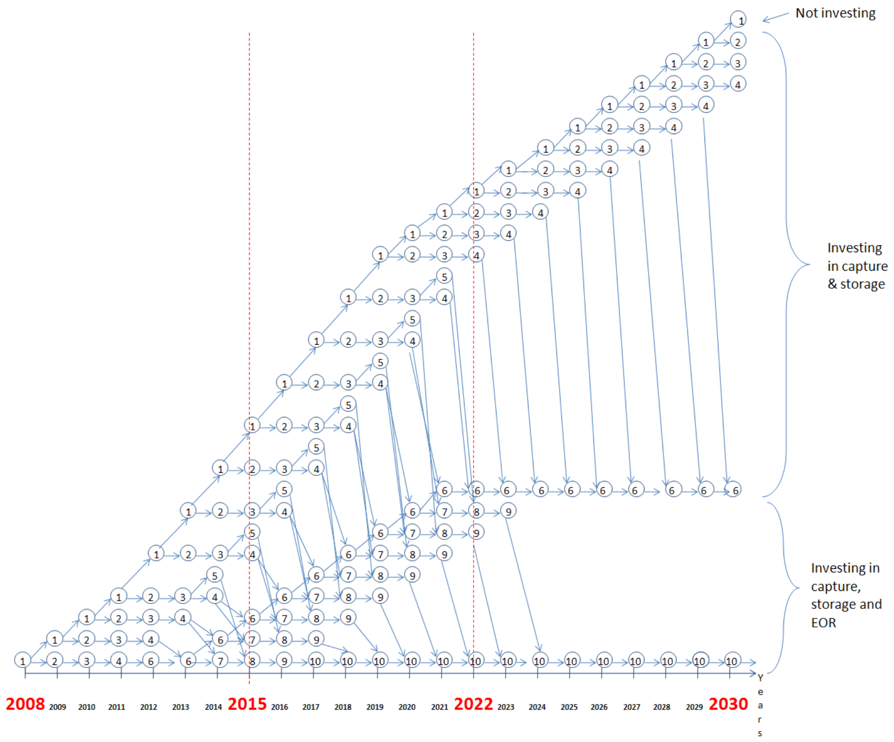


Figure 12: *State diagram for investment states*

5.2.3 A decision tree approach

We are now to illustrate how the investment states and the price nodes work together, through a decision tree. Uncertainty is resolved and the decisions are made sequentially. In the stochastic dynamic program, a decision needs to be made in each stage, which in this thesis corresponds to a time period. The decision is on which state to go to, i.e. which actions to undertake.

Because the entire decision tree is too large, an example decision is illustrated in Figure 13. Expected payoffs are usually shown, to be able to solve the problem via such a tree only. This is called a decision tree approach. The figure shows the decision problem in time period 2, given the system is in state 1. In this state the options are to invest in capature or wait. Investing in capture means going to state 2, whereas waiting means staying in state 1. The direction which provides the highest expected profit should be chosen. *After* the decision is made, the crude oil price and the CO_2 quota prices are revealed. There are here four outcomes of prices, see explanation in section 5.2.1. The resulting prices influence the future profit. From analyzing a complete decision tree, it is possible to make an investment decision, based on which path that provides the best expected profit. (Wallace 2002)

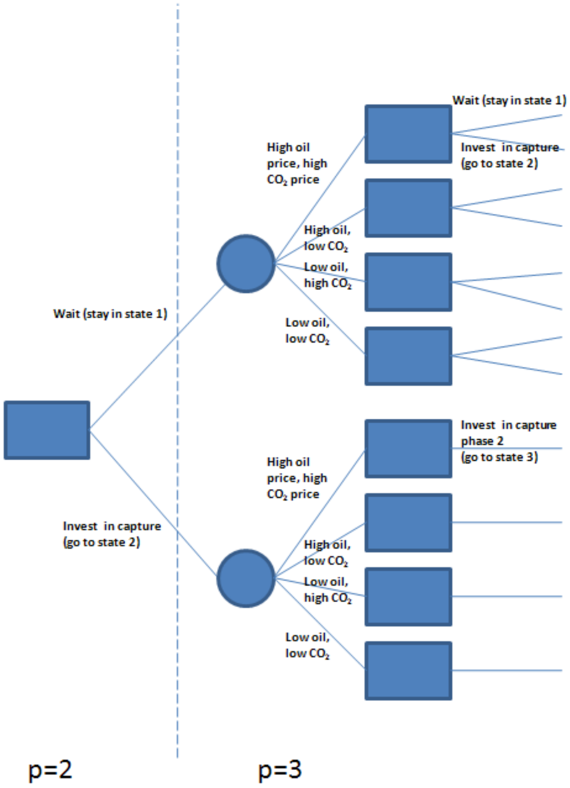


Figure 13: *Part of the decision tree: Standing in state 1, time period 2*

5.2.4 Mathematical model - SDP

This section will describe the main features of the mathematical stochastic dynamic program that is made for this thesis. The sets and constants that are essential for the following pseudo-code are firstly introduced. The complete code that is programmed in XpressMP is given in G.

Indices

p	time periods $\in \{1..P\}$
i	states $\in \{1..I\}$
n	nodes giving scenarios for crude oil and carbon prices $\in \{1..N\}$

Constants

$SLOG_{ii'p}$	$\begin{cases} 1 & \text{if the state transition from } i \text{ to } i\text{'} \text{ is allowed from period } p \text{ to } p\text{+}1 \ [-] \\ 0 & \text{otherwise } [-] \end{cases}$
$NLOG_{np}$	$\begin{cases} 1 & \text{if node } n \text{ is possible in period } p \ [-] \\ 0 & \text{otherwise } [-] \end{cases}$
$NPROB_{nn'}$	The probability of moving from price scenario n to price scenario n' $[-]$ *
$CAPEX_{ip}$	Investment cost in state i and period p $[mill\,EUR]$
$OPEX_i$	Operational costs in state i $[mill\,EUR/year]$
PO_n	Crude oil price in price scenario n $[mill\,EUR/barrel]$
PC_n	CO_2 price in price scenario n $[mill\,EUR/Mtonnes]$
OIL_{ip}	Extra oil production in state i and period p $[barrels]$
$CO2_{ip}$	Amount of released CO_2 in state i and period p $[Mtonnes]$
INF	Inflation rate $[-]$
r	Discount rate $[-]$

*) $NPROB_{nn'}$ *is in reality time dependent, but because of the nature of the problem, this is given implicitly.*

Model output

Π_{inp}	The future profit** for state i in price scenario n and period p $[mill\,EUR]$
ΠOPT_{inp}	The optimal future profit when being in state i in price scenario n and period p $[mill\,EUR]$
$BEST_{inp}$	The state to go to when being in state i in period p and price scenario n to obtain the optimal future profit $[-]$
$E\Pi OPT_{inp}$	The expected optimal future profit (from period p and onwards) when being in period $p-1$ with price scenario n and going to state i in the next period (p) $[mill\,EUR]$

**) *The future profit is the profit generated in the time interval* $[p, P]$.

The future profit function for each time period is given by the sum of the profit from the actual time period (investment and operational costs minus the revenues) plus the expected profit from the coming years until the end of the time horizon. The expression for the future profit is given in equation 17 (adjustment for inflation is not included here).

$$\Pi_{inp} = -CAPEX_{ip} - OPEX_i + PO_n \cdot OIL_{ip} - PC_n \cdot CO2_{ip} + \frac{1}{1+r}\sum_j (E\Pi OPT_{jn(p+1)}) \tag{17}$$

where

$$E\Pi OPT_{jn(p+1)} = \sum_{m|NLOG_{np}=1} NPROB_{nm} \cdot \Pi OPT_{jm(p+1)} \tag{18}$$

For the last time period (period P) the last element of Equation 17 will be zero and the (optimal) profit can be calculated for each combination of state and price scenario. These values are used as input data for the backwards stochastic dynamic program. The pseudo-code of the main part of the SDP is given in the box below.

```
Initialisations
$\Pi OPT_{inp} := -\infty$
$\Pi OPT_{inP} := -CAPEX_{iP} - OPEX_i + PO_{in} \cdot OIL_{iP} - PC_{in} \cdot CO2_{iP}$
$p := (P-1),\ i = 1,\ n = 1,\ j = 1$
Repeat: until $p = 1$
  Repeat: until $i = I$ and $n = N \mid NLOG_{np} = 1$- RIGHT?
    Repeat: until $j = J \mid SLOG_{ijp} = 1$
      Calculate: $E\Pi OPT_{jn(p+1)}$
      Calculate: $\Pi_{inp}$
      If $\Pi_{inp} > \Pi OPT_{inp}$
        Update: $\Pi OPT_{inp} := \Pi_{inp}$ and $BEST_{inp} := j$
Output: $BEST_{inp}$and $\Pi OPT_{inp}$
```

The annual amount of extra oil that is recovered when investing in EOR depends on the year in which EOR was started. Because of this, the SDP is not as simple as described in the pseudo-code in reality. Only state 10 will be affected by the revenue from extra oil. Some adjustments are therefore done for state 9 and 10 to satisfy this special property of the problem. The way this is modelled is described more systematically in Appendix C.

It needs to be mentioned that risk neutrality is assumed since the expected value is maximized in the investment problem.

5.3 Monte Carlo simulation

As a tool for analyzing the results from the stochastic dynamic program, Monte Carlo simulation is implemented. It will be used for the sake of visualizing the possible future outcomes of prices in a good way.

Monte Carlo simulation is a way to sample random variables from complicated probability density functions. For the analysis, such simulations are used to generate price paths for carbon and crude oil in 50 000 future scenarios. In this section the simulation method is described. The XpressMP code for the simulations are to be found in Appendix G and the results are given in section

6.

5.3.1 The Inverse Transform

The Inverse Transform is a general methodology for generating samples of both continuous and discrete distributions. As described in section (5.2.1) the crude oil and the CO_2 prices are modelled as a recombining non-rectangular tree (discrete) in this thesis. Only the Inverse Transform method for discrete distributions will therefore be described here. For further theory about Monte Carlo Simulation and the Inverse Transform see (Dagpunar 2007) or (Yao et al. 2006).

Given the following information (Dagpunar 2007) :

- X is a discrete random variable with cumulative distribution F, $x = \{0, 1, ...\}$. The probability of x is p_x.
- R is a continuous random variable that is uniformly distributed in the interval (0,1) ($R \sim U(0,1)$).
- $W = min\{x : R < F(x),\, x = 0, 1, ...\}$

Because $W = x$ if and only if $F(x-1) \leq R < F(x)$ the cumulative distribution function of W will be F. The probability of this happening is $F(x) - F(x-1) = p_x$. The Transform Inversion Method is shown graphically in Figure 14.

One simulation includes generating one R for each time step. The belonging W's will give the price path for this simulation.

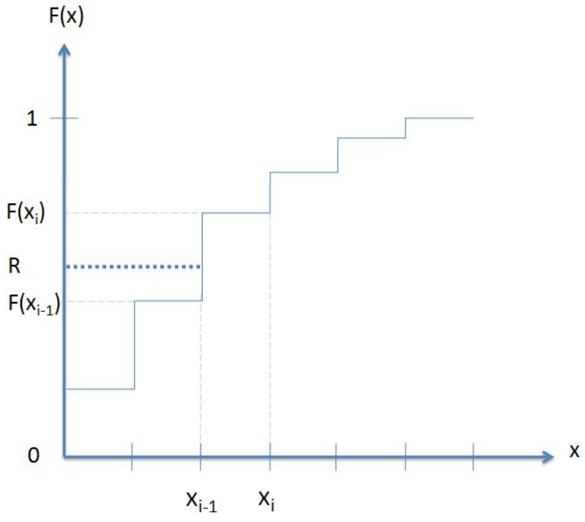


Figure 14: *The Transform Inversion Method (Yao et al. 2006)*

5.3.2 Mathematical model - Monte Carlo simulation

How the Transform Inversion Method is modelled is given in the box below. Some further elements that are relevant for the modelling of the simulation are introduced first. See section (5.2.4) for indices and parameters which are already defined.

Indices

s	simulations $\in \{1..S\}$

Constants

$CNPROB_{nn'}$	The cumulative probability of moving form price scenario n to price scenario n' $[-]$

Model output

SPO_{sp}	The price of crude oil in period p in simulation s $[mill\,EUR/barrel]$
SPC_{sp}	The price of CO_2 in period p in simulation s $[mill\,EUR/Mtonne]$
SN_{sp}	The price scenario node that is present in time p in simulation s $[-]$

```
Initialisations
$s = 1,\ p = 1,\ n = 1$

Repeat: until $s = S$ and $p = P - 1$

    If $p = 1$

        Set: $k := 1$ and $SN_{sp} = k$

    $R := random(0, 1)$

    Initialise: $n = 1$

    Repeat: until $(n = N \mid NLOG_{n(p+1)} = 1)$ or the If-condition is satisfied

        If $CNPROB_{kn} > R$

            Set: $SN_{s(p+1)} = k$ and $k := n$

Output: $SN_{sp}$
```

5.4 Input data

The input parameters of the stochastic dynamic model are summarized in tables in Appendix D. Some of the values are commented on in the following. All monetary parameters are adjusted for inflation and converted to EUR of year 2008. Where nothing else is mentioned, assumptions concerning costs and other input data is set in accordance with Tore Torp in StatoilHydro(Torp 2008).

It is important to note that the costs used in this analysis are based on information from the actors. Hence, the costs reflect what the actors are willing to share. This may cause inaccuracy. The actors may use the cost estimates they give as a measure of influencing the decisions in the value chain. Inaccurate cost estimates may often lead to other solutions (worse) than the solution given correct costs.

5.4.1 Price adjustments

The cost data taken from years before 2008 is adjusted according to rise in prices. For the CAPEX (investment costs) of capture the Chemical Engineering Plant Cost Index (CEPCI) is used[12]. For pipelines, a specific CEPCI for pipelines should ideally be used. As we do not have this number from 2005, the CEPCI annual index is used instead, which is a weighted sum of many categories, including pipelines.

---

[12] www.che.com (visited April 2008)

The CEPCI for November 2007 is used as an approximation for the 2008 value. The value has however not changed much over such a short period. The following calculation is used:

$$CurrentCost = \frac{CurrentCEPCI}{CEPCI(t)} * Cost(t) \tag{19}$$

In the CEPCI index inflation is integrated. The OPEX (operating costs) for capture is set in accordance with the current natural gas price, as this component represents a large amount of the cost. The injection well cost is regulated according to an index for offshore upstream investment presented by the International Energy Agency in (IEA 2008).

5.4.2 Time horizon

The years we consider in the model are the years from 2008 through 2030. The reason for this is that a potential EOR period for Heidrun is assumed to be ended in 2030. The lifetime of the natural gas power plant (Tjeldbergodden) is assumed to be about 25 years, starting from year 2008.

5.4.3 Cost parameters

Capture

The capture costs are taken from a report written in 2005 by StatoilHydro and Flour concerning the mapping of consequences of Tjeldbergodden (StatoilHydro and Fluor 2005). The CAPEX of capture includes parts and equipment, construction work, land lot and planning, and cost of unpredicted events and uncertainty. The post-combustion method is the basis for the estimate. The planned gas power plant at Tjeldbergodden, together with the possible capture plant, is shown in Figure 15. At the time of the report, there was not yet built a full scale capture plant, used for a natural gas power plant. This adds uncertainty to the values. In lack of more recent cost estimates, we use the 2005 number as an estimate for year 2008. Capture cost values generally differ strongly from year to year, and from study to study.

Efficiency for the capture installation is assumed to be 85%. The efficiency of the power plant will be lowered when installing a CO_2 capture plant. This should in principle be integrated as a loss in our model, but is not considered. Flour (StatoilHydro and Fluor 2005) has assumed that the CO_2 at Tjeldbergodden is compressed to achieve a pressure of 100 bars and that it is dried before being exported through pipelines.

Severe uncertainty is connected to the CAPEX of capture. Results from 'The CO_2 Capture Project, Phase 1' (CCP 2004) express that capture cost will possibly be reduced extensively in near future because of research. For the post-combustion technology called 'Best Integrated Technology' the cost is estimated to be halved within 2010, if development work continues. A rough estimation for the technology development is made for our capture case. The investment cost of capture is set to be constant until 2010, and then given a 50 % linear reduction within 2020, followed by a constant level for the remaining years, until year 2030. The argument is that, assuming that present conditions in energy and labor costs are representative for the future conditions, the technology costs behind the capture is assumed be halved during those ten years. Due to increased public attention around CCS, together with the EU working towards their 2050 goal, it is supposed that the technology development will speed up in the time to come. In this matter, the *timing* of the capture investment might be crucially important. On the other hand, the CAPEX of capture may rise during the same period, due to the increasing CEPCI index. A lack of skilled personnel is the major reason behind the CEPCI being so high currently. It is not for sure that this issue is going to disappear in near future.

For capture we have assumed an investment plan of paying 20% of the total cost the first year, and 40% the two following years. With decreasing investment cost, the capture cost for the *first* investment year is used as a basis for the following years. For instance, if investment start is in year 2010, 20% of this cost will be paid in 2010, whereas 40% out of the 2010 cost will occur in 2011 and 2012.

OPEX for the capture plant is taken from the same study, and includes staffing, maintenance, chemicals, taxes and insurances as well as energy costs. Since the natural gas price of April 2008 was as high as 10.2 \$/MMBTU[13], the OPEX is set to its highest level, described by (StatoilHydro and Fluor 2005).

Since we suppose that the power plant Tjeldbergodden starts operation in 2008, the time horizon will capture almost the whole lifetime of the plant. When it comes to the capture plant the investment in this is flexible and can be made at any point during the power plant lifetime. The capture plant is supposed to have no worth when the lifetime of the power plant is over. In this perspective, the investment of capture will only be of value until the end of the time horizon. We consider the end of the lifetime and the end of the time horizon to be so similar that we disregard reduction of costs according to the percentage of the lifetime we look at.

---

[13] www.nymex.com (visited April 16th 2008)

Figure 15: *Tjeldbergodden: The planned* CO_2 *capture plant, to the right of the planned power plant (StatoilHydro and Fluor 2005)*

EOR

The CAPEX cost of Heidrun is set to 25% of a well cost[14]. This should approximate the total cost of enabling for EOR, including a compressor used for increasing the pressure of the CO_2 that is reproduced with the gas produced, so that it may be re-injected for EOR again.

The OPEX for the recompletion is set to 5% of CAPEX, which is reasonable for offshore installations.

The revenue from EOR is based on the yearly amount of extra oil produced. As explained in section (4.2.2), this amount exclusively depends on the year EOR is implemented.

Separation plant

The CAPEX and the OPEX of the separation plant at Heidrun are set equal to those of the capture installation at Tjeldbergodden, since it represents the same technology.

---

[14] The injection well will be a recompleted production well.

Storage

The CAPEX of the injection well at the Alpha structure is based on an estimation from the Norwegian Water Resoucres and Energy Directoreate (NVE 2005).

OPEX of the storage site is set to a fixed, annual fee, starting in the storage investment year. The OPEX is not directly connected to operation of the well, but represents continuous supervision concerning potential leakage. The supervision cost does not vary with the volume stored.

Transportation

SINTEF has implemented a study on Tjeldbergodden using a 14 inches pipeline between Tjeldbergodden and Heidrun based on an annual volume of 2.1 Mtonnes of CO_2 (SINTEF 2005). We use their CAPEX of the pipeline as an approximation. The characteristics of the pipeline between Alpha and Heidrun, over a distance of about 80 km, should be equal to those of the other pipeline, since they are connected. The pipeline cost of Tjeldbergodden - Heidrun is used as a reference to find a pr. km. cost, which in turn is used to multiply by the distance Alpha -Heidrun.

OPEX of the pipelines is assumed to be 1% of CAPEX.

5.4.4 Residual values

The residual values for pipelines, capture plant, injection well and EOR installations are all set to zero. The reasoning behind is that if such a value is discounted over as much as 23 years, it would result diminishingly small. In practice, some of the installations might have value for other purposes. The pipeline could for instance be used for natural gas, and could thus be assigned a residual value of about 10%. We have anyhow not used any residual values in this thesis.

5.4.5 Input parameters for the stochastic modelling

For input parameters to the non-rectangular tree, representing the stochastic oil and carbon prices, forecasts from recognized actors are used and will be introduced in this section. Forecasting reliable oil and carbon prices is not within the objective of this thesis.

Crude oil prices

Crude oil price forecasts from the US Energy Information Administration (EIA) Energy Outlook 2008 (EIA 2008) are used in the model for the expected drift of the geometric Brownian motion.

This forecast is based on the assumption that the policies that affect the energy sector remain unchanged (from the current status in 2008) (EIA 2008) . This is a rather rough assumption, especially when considering that the adoption of policies to reduce greenhouse gas emissions may change the projections significantly.

The crude oil price forecast from EIA gives drift parameters that vary with time. For the non-rectangular tree representing the stochastic prices (see section 5.2.1) the drift parameter has to be constant throughout the whole time horizon. A simplification is therefore done by using values from the EIA forecast for the first year (2008) and the last year (2030) of the time horizon in our model, to calculate one mean annual drift parameter.

The standard deviation for the crude oil price is set to 7.75%. This is the same as Yang and Blyth use for all energy prices (except coal) in a working paper for the International Energy Agency (Yang and Blyth 2007). They also model energy prices as geometric Brownian motions for investment problems with long time horizons.

Carbon prices

The carbon market has not existed long enough to make it possible to provide reliable price development forecasts built on historical data. There are still several global actors that deal with the issue. Most of the forecasts are however not published. As input parameter for our model, forecasts from Deutsche Bank (DB 2007) is used. The DB price target, for both Phase I (2008-2012) and Phase II (2013-2020) EUAs[15], is set to a constant value of 35.0 EUR. Because of the uncertainty related to the years after 2020, it is decided to extrapolate this forecast for the remaining years.

The drift parameter for the carbon price is therefore set to zero in the model, as the forecast is constant. As for the crude oil prices, the standard deviation for carbon prices is taken from (Yang and Blyth 2007) and set to 7.75%.

Assuming that there is no value for any company to avoid greenhouse gas emissions, the carbon price is only created by government policy. The uncertainty in carbon prices should therefore be studied in relation to uncertainty in future government climate policy. Changes in climate policy could have been modelled as discrete shocks in the carbon price at specified points in time when policies change. An application of this can be found in (Yang and Blyth 2007). Yang and Blyth model the carbon price as a jump with the range ±100% and a flat probability density within this range.

Price correlation It is assumed that the carbon price will follow the crude oil price to a certain degree, which means there is a positive correlation between the

---

[15] European Unit Allowances

two prices. Based on data from Italy[16], (Yang and Blyth 2007) suggests 0.87 as the correlation factor. The same correlation factor is used in the analyses this thesis. Because the factor is based on historical carbon price data (on which it is hard to build reliable forecast), the future validity of it is extremely uncertain. The effect of the correlation factor on the investment decisions is therefore studied in the sensitivity analysis in section 6.7.

5.4.6 Other input parameters

Discount rate

The discount rate should reflect the perspective of the analysis, namely maximizing the profit of the whole value chain, i.e. the profit potential which lies in the value chain for the society to take advantage of. Hence we look to (NMF 2005b) and the belonging (NMF 2005a) made on behalf of The Norwegian Ministry of Finance for advice on estimating a socio-economic discount rate. Taking the purpose of our analysis into account, this approach seems good even though our analysis is not a complete socio-economic analysis.

The discount rate consists of two parts, a risk-free rate and a risk-adjustment. It expresses the socio-economic cost of long-run capital engagement. The risk-adjustment depends on the economic risk of the project and thus on the nature of the project.

In (SFT 2005) The Norwegian Pollution Control Authority (SFT) employs a risk-adjusted rate of 7 % for projects concerning CO_2 capturing for storage and EOR, which should involve the same level of risk as our value chain. The risk-free base rate of this rate is however 3.5 %. After (SFT 2005) was written, the Norwegian Ministry of Finance adjusted the risk-free rate from 3.5 % to 2 % (NMF 2005a). The risk adjustment from SFT is 3.5%. Using the recommended risk-free rate of 2% and the risk adjustment SFT used for a similar project of 3.5%, we apply a discount rate of 5.5%.

This rate is lower than what is often applied for such projects (around 7%). The reason is that the adjustment from the Norwegian Ministry of Finance is rather recent. We find it however reasonable to follow their guidelines. It should be kept in mind that the level of the discount rate plays a role, and that changes of the rate might change the result.

Inflation rate

The Norwegian Government's monetary policy is to keep the inflation stable at about 2,5%[17]. We have therefore applied this inflation rate.

---

[16] Italy is the only state in the OECD that uses oil for power generation. The correlation factor is calculated from national average data from Italy.

[17] www.norges-bank.no

6 Results

In the results section we present and analyse the investment decisions proposed by the model for the the discussed value chain. Because of the stochastic parameters in the model, no single optimal investment sequence is proposed by the model. It is therefore not possible to plan for the whole period ahead of time. The model gives the optimal strategy, adapting the value chain investments to the uncertain future realization of oil and CO_2 prices. Only the decision for the first time period is deterministic, while decisions for all other time periods depend on how the uncertainty resolves.

There are two main investment decisions that can be made in the given value chain during the given time horizon. The first is whether to invest in a CO_2 capture plant or to wait. This decision can be made throughout the whole time horizon. If the decision to invest in a capture plant is made, there are three main options available for the rest of the time horizon: to invest in enhanced oil recovery (EOR) as soon as possible, to store the CO_2 throughout the time horizon without implementing EOR or to store the CO_2 for some years followed by EOR. Investment in storage facilities is carried out if the capture decision is undertaken[18]. The second investment decision is then whether to invest in EOR or to wait. Waiting thereby refers to storage.

It should be noted that the gas power plant is assumed to be operating regardless of the discussed value chain.

We will now define some notation which is used throughout the results section without further explication:

- *The base case* is the case where all input parameter values are those presented in section 5.4, and which is the case we actually examine in this thesis
- The *expected profit* represents the expected net present cash flow from period t to the end of the time horizon if going from state x in a time period t to state y in $t+1$ based on the prices in time t and the expected future development of these.
- A *price path* refers to one specific development of crude oil and carbon price over the time horizon and consists of exactly one price node for each period.
- An *investment path* refers to one sequence of investments throughout the time horizon.
- *The investment rate* refers to the percentage of the simulations where investment occurs.

---

[18] If EOR is implemented, a slip stream will be directed to storage due to re-production of CO_2 from the field. If EOR is not implemented all captured CO_2 is directed to storage.

- *The timing decision* refers to the choice of investment path.
- A *strongly dominant investment path* refers to a path that is optimal for more than 90% of 50 000 simulations.
- A *very strongly dominant investment path* refers to a path that is optimal for more than 95% of 50 000 simulations.
- When an investment decision is *made* in a year, the actual *start of construction and investment cost* occur in the following year.
- When the decision to invest in EOR is made in year y, the actual injection of CO_2 to the reservoir is done in year $y+2$.
- When the decision to invest in a capture plant is made in year y, the actual capture of CO_2 will occur in year $y+4$ (because of three years of construction)
- When the decision to invest in a capture plant is made in year y, the next decision (whether to invest in EOR or wait (store)) takes place in year $y+2$

See also section 5.2.2 for more information on states and transitions between them.

The reader should also keep in mind the important assumption that EOR injection can only be started in the interval 2015 to 2022. This assumption makes 2018 the last year in which the decision to invest in capture plant can be followed by EOR.

The structure of the results section

This section starts with a brief description of the software specification and problem size. The results from a convergence analysis and a validity test are then discussed to support the stability of the stochastic dynamic program and validity of the Monte Carlo simulations respectively. The value and impact of the implementation of flexibility and uncertainty for the case in question is further analysed. The main findings of the results are separated into three main sections; investment decision rules, results from simulations and sensitivity analysis.

6.1 Software specification and problem size

For solving the stochastic dynamic program, the optimization tool XpressMP version 2.2.0 from 2007 is used, with mmive version 1.185. The computer used has a CPU of 2.8 Hz with 504 MB of RAM. Microsoft Windows XP Version 2002 is the operating system. The computer runs using a 32 bit system.

The XpressMP program code, given in G, solely consists of calculations in loops and thereby no optimization. Programs such as C or Matlab may therefore also have been applied. The effect this might have on calculation time is not further investigated.

The stochastic dynamic program is characterized by a tree size of 28 343 nodes. The time discretization is that of one year, and a time horizon of 23 years makes the problem have 23 steps. As a decision is taken every year, the problem has 23 stages, equal to the steps. There are two state variables; the carbon price and the crude oil price. When running 50 000 simulations, the calculation time is 6 minutes and 48 seconds. Without simulations it takes 57 seconds to run the model.

6.2 Validity test

In section 6.6 the results from the Monte Carlo simulation will be presented. To decide on the appropriate number of simulated price paths to execute, a validity test is carried out with different simulation sizes. To decide whether a chosen number of simulations is sufficient, 50 runs are implemented and the mean optimal net present value (NPV) of the 50 runs are calculated. As a requirement for the Monte Carlo simulation to be valid, the mean NPVs of the 50 observations should be within a certain range. In practice this implies the requirement that the results from running the model should not differ too much for the 50 runs.

Tests are carried out for 20 000 and 50 000 simulations. For each of these the confidence interval is calculated based on one randomly picked run from the 50 runs, meaning that these simulations represent the normal distribution from which the 95% confidence interval is created. The resulting confidence intervals are shown in Table 2. By implementing 20 000 simulations, three mean optimal NPVs are outside the confidence interval, which constitute 6% of the observations. Only two of the mean optimal NPVs are outside the interval when implementing 50 000 simulations, constituting 4% of the observations.

Acceptance of deviations should be compared to the least accurate parameter of the model. No further investigations are implemented concerning which parameter this is. On of the considerable costs in the model is the CAPEX of capture. It has in earlier studies been subject to vast differences in its cost estimate. In (NVE 2005) different estimates are mentioned, and one of the numbers deviates by 524 mill EUR from the one used in this thesis. Since the NPV of the CO_2 value chain investment in reality could vary with such an amount, the variation of NPVs from the 50 runs are much smaller and should thus be accepted. Based on this perspective, both 20 000 and 50 000 simulations could have been used. Since calculation time is still very low for 50 000 simulations, we anyhow choose to go further with this.

The distribution of the mean optimal NPVs of the 50 runs with 50 000 simulations are illustrated in Figure 16. It seems that the values are more or less normally distributed around their mean value of -191 mill EUR.

	Minimum [mill EUR]	Maximum [mill EUR]
NPV, 20 000 sim.	-196	-180
NPV, 50 000 sim.	-195	-185

Table 2: *95 % confidence intervals*

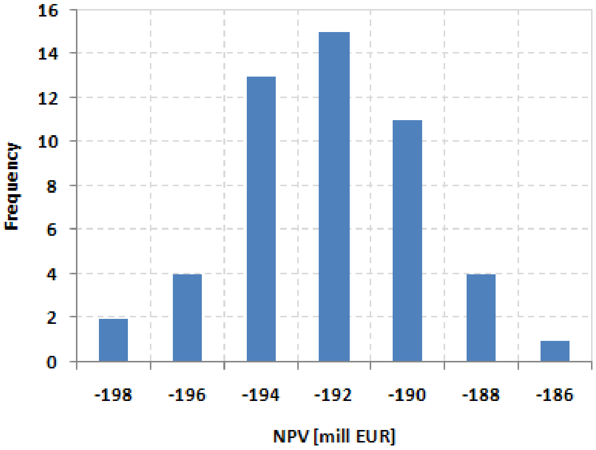


Figure 16: *Distribution of 50 NPVs*

6.3 Convergence and stability of stochastic prices

The stochastic carbon and crude oil prices are assumed to follow geometric Brownian motions (GBM) as explained in section 5.2.1. As an approximation of these motions the prices are expressed as discrete price combinations in a non-rectangular tree in this thesis. To test the stability of the discrete approximation of the GBM we do a convergence analysis.

The reader should be confident with how the non-rectangular tree is built and familiar with the nomenclature used in section 5.2.1 before reading this section.

The time horizon is divided into N sub-intervals of length dt. The non-rectangular tree branches at time idt, where $0 \leq i < N$. The smaller the dt is, the more price nodes are present in the non-rectangular tree. In the limit as dt tends to zero, the discrete prices imitate the continuous GBM, and the exact value of the real option is obtained.

For the case presented in this thesis the time horizon is 23 years and N is set to the same number in the investment model, giving $dt=1$. To see if this is a satisfying number to make the tree a good approximation of the GBM, the problem is additionally solved with $dt=0.5$ and $dt=2$. The results are given in Table 3 and shown in Figure 17. We observe that the absolute value of the slope is significantly smaller for the graph between the points for 23 and 46 steps than between 12 and 23 steps. This might indicate that the value of the real option is moving towards an asymptote. The implemented number of step size is based on this seen as acceptable for the purpose of this thesis. We can not conclude from these results that the real option value actually reach an asymptote here or if it keeps going down when N increases. More values of N must be implemented to assure this. Increasing the number of time steps further require high calculation times.

Step size dt	Number of steps N	Real option value [mill EUR]
2	12	-186
1	23	-191
0.5	46	-192

Table 3: *Results from convergence analysis*

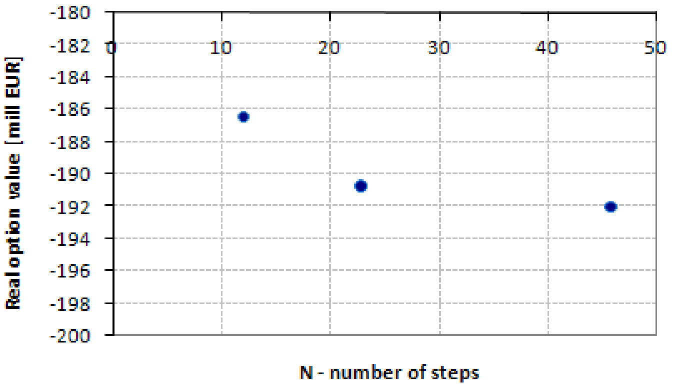


Figure 17: *The real option value at different number of time steps*

6.4 The impact of flexibility and uncertainty

The stochastic dynamic program (SDP) which represents the value chain model in this thesis has two properties whose impacts should be evaluated; the flexibility implemented by the (backwards) dynamic programming, and the uncertainty which is implemented as a stochastic process. More specifically, the investment timing is dynamic, and the crude oil and carbon prices are stochastic. Such a model is more complex and thereby more expensive than simpler models. Hence, it is interesting to see whether better results are derived when these aspects are accounted for, and thereby if they are worthy of implementation.

6.4.1 The impact of flexibility

We want to evaluate the impact of letting the investment timing be flexible within the given set of time restrictions, i.e the impact of using a dynamic model as opposed to a static model. We will perform this evaluation by comparing the value of the real option of the SDP with the corresponding value of static investment paths (under stochastic conditions). For static investment paths this value is the NPV of a pre-decided path. For dynamic investment paths this value is the expected NPV taking into account the stochastic development of prices. In Table 4 the NPV of investment paths are shown for the following cases:

- no capture plant is installed (carbon quotas purchased throughout the time horizon)
- capture and EOR are installed as soon as possible (capture investment decision in 2008, EOR investment decision in 2013)
- capture is installed immediately, EOR as late as possible (capture investment decision in 2008, EOR investment decision in 2020)
- capture is installed immediately, no EOR (capture investment decision in 2008)
- capture is installed immediately, EOR timing is optimized (capture investment in 2008, EOR investment in 2019)

Capture decision	EOR decision	NPV [mill EUR]
Never	Never	-1 190
2008	2013 (as soon as possible)	-849
2008	2020 (as late as possible)	-594
2008	Never	-2 060
2008	2019 (dynamic EOR timing)	-594

Table 4: *NPVs of different investment paths*

The expected NPV of the SDP, namely the dynamic solution, is the one to compare with the NPVs from the static solutions. The value (-191 mill EUR) is clearly better than the static results. In this comparison it should be noted that no static solutions are done for postponed capture investment, which we will see later that dominates the solutions in the SDP. This means that the flexibility of the investment timing is valuable. Postponing the investment chain is better than both starting it immediately or rejecting it.

Some simple conclusions may be drawn from the results in Table 4. In an analysis based on immediate capture investment, the best expected NPV which may be obtained is -594 mill EUR. In a static perspective this will only be found if the particular path giving this value is investigated. It is not unlikely that another year would have been chosen for EOR investment due to other factors, failing to see the fact that year 2020 was better. If for instance the value chain was to be implemented as soon as possible, the NPV would have been -849 mill EUR. This implies that the EOR timing influences the profit obtained throughout the value chain.

Furthermore, the profit from investing in capture now is worse than that of investing in capture later. We know this because the the results of the SDP give, close to independently of the realisation of uncertainty, capture investment in year 2019 and an expected NPV of -191 mill EUR. Thus, the dynamic result is 67.7 % better than any result which might have been obtained if capture was a “now or never-”decision. The flexible timing of the value chain is thereby very valuable. This emphasizes the importance of the main purpose of this thesis; namely to evaluate the investment timing for the value chain.

In an NPV based now-or-never-perspective, it is worth commenting on the fact that capture would have been chosen now because NPV of rejecting the project (purchasing carbon quotas) is worse than the NPV of the investment chain. Using the NPV method would, as opposed to the real option valuation, thus recommend investment now. This would remove the opportunity of realizing the optimal investment timing; namely that of delaying the investment for some years.

6.4.2 The impact of uncertainty

We want to evaluate whether the implementation of uncertainty in crude oil and carbon prices is valuable for the investment timing problem. We find the deterministic results by removing the volatility in prices from the dynamic model. The optimal investment paths are the same for the stochastic and the deterministic cases. Hence, the consideration of price uncertainty does not affect the timing decision, and the implementation of this uncertainty gave us no further insight than the deterministic.

The NPVs of the deterministic and stochastic cases are however marginally different; the one for the stochastic case of -191 mill EUR is 0.59 % better than the deterministic NPV of -192 mill EUR. The stochastic approach give a slightly more optimistic view. The small deviation may indicate that the upside of the stochastic case is greater than its downside.

6.5 Decision rules for investments

It is of interest to see which factors that affect the timing decisions. The results from the stochastic dynamic program are used to analyse the levels of carbon and oil prices that are present in years where the different investment decisions take place. This section studies the optimal investment decisions in the possible price combinations for different time periods.

The possible price combinations are given by the non-rectangular tree. The further out in the time horizon the year is, the higher is the number of possible price combination, and the higher is the spread in the prices. This is explained in detail in Section 5.2.1. The reader should keep in mind that there are different probabilities for being in the different price combinations within a time period. Shares of the price nodes may therefore not be related to the probability of these prices to be present.

6.5.1 The decision to capture CO_2

Figure 18 illustrates some of the results from the analysis related to the first investment decision, whether to build a capture plant or to wait. Because an investment decision depends on the present year in addition to the present prices, each of the diagrams given in Figure 18 shows the results connected to one specific year. The blue spots in a diagram represent the combinations of carbon and crude oil prices where the optimal decision is to wait (not invest) in that specific year. The orange spots are the price combinations where it is more profitable to invest than to wait. The blue and orange spots together represent the total amount of possible combinations of prices in that time period.

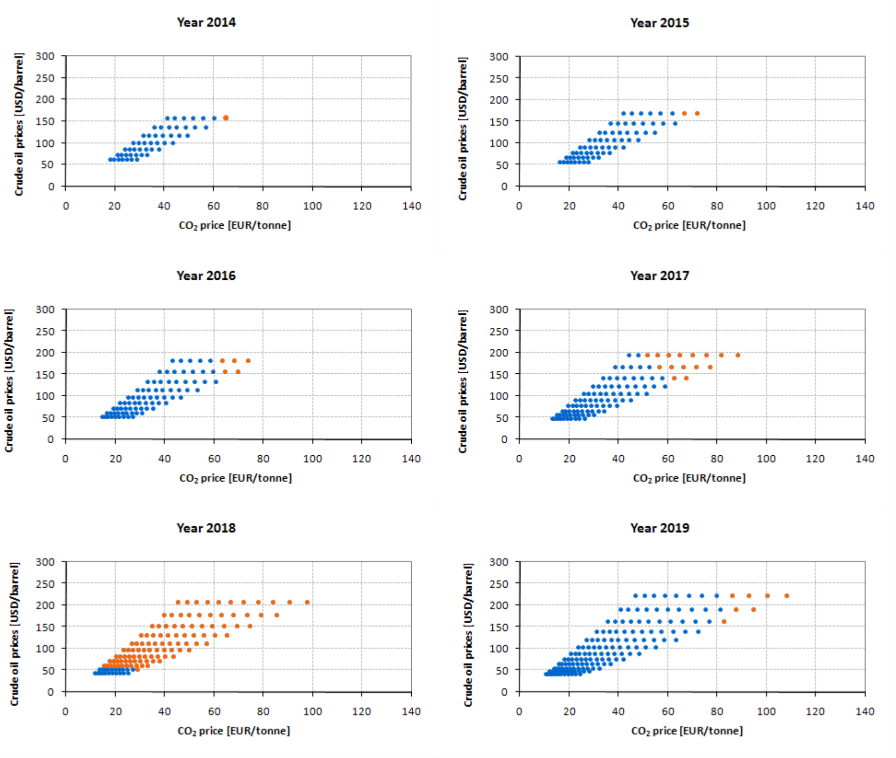


Figure 18: *Crude oil and carbon prices related to capture investment*

Figure 18 only presents the results from the years 2014 through 2019. It is not profitable to invest in capture plant in any of the previous years (2008-2013), independently on the carbon- and crude oil prices. Within these periods the carbon price is never higher than 87.1 EUR/tonne CO_2 and the crude oil price is never higher than 148 USD/barrel. From this it can be concluded that as long as the prices are below these levels (87.1 EUR/tonne CO_2, 148 USD/barrel crude oil) during the years 2008 through 2013 it is more profitable to wait than to invest in capture plant. As we can see in Figure 18 investment is the optimal choice in some of the possible price combinations in the years 2014 through 2025. A first obvious observation is that the investments take place in price combinations with high carbon prices and high crude oil prices. It is noteworthy that the level of prices where investment is optimal is not the same for different years. A clear examples is for year 2018 where it is optimal to invest in significant lower prices than in previous years.

2018 is the last year in which the decision to invest in capture plant can be followed by EOR. In this year we can see from Figure 18 that investment will be the best decision in the majority of the possible price combinations. An observation from this fact is that if the decision to invest has not been made before 2018 investment will for most of the price combinations take place here.

From year 2019 through year 2025 investment in capture can only be followed by CO_2 storage. Investment is still the best choice in some of the price combinations in these years. The results indicate that investment only takes place in extremely favorable price combinations. From year 2026 until the end of the time horizon (2030) investment is not profitable for any combination of prices. This is a rather obvious result because if investment is done in 2026, there will only be one year of quota exemption. The savings from this will not exceed the investment costs. If investment is done in later years, no quota exemption will be found.

The decision rules, for whether to invest in capture plant or to wait, are given in Table 5.

	Invest if:		Wait if:	
Year	**CO2 price [EUR/tonne]**	**Crude oil price [USD/barrel]**	**CO2 price [EUR/tonne]**	**Crude oil price [USD/barrel]**
2008-2013	Never	Never	Always	Always
2014	> 64.8	> 158	< 64.8	< 100
2015	> 66.5	> 170	< 66.5	< 170
2016	> 63.3	> 156	< 63.3	< 156
2017	> 51.6	> 143	< 51.6	< 143
2018	> 15.5	> 51.5	< 15.5	< 51.5
2019	> 82.7	> 163	< 82.7	< 163
2020	> 88.3	> 175	< 88.3	< 175
2021	> 94.0	> 187	< 94.0	< 187
2022	> 104	> 200	< 104	< 200
2023	> 120	> 214	< 120	< 214
2024	> 144	> 268	< 144	< 268
2025	> 200	> 335	< 200	< 335
2026-2030	Never	Never	Always	Always

Table 5: *Decision rules, capture investment*

6.5.2 The decision to start EOR

If the decision to invest in capture plant is made, the next decision is whether to use the CO_2 for EOR or not. If investment in capture plant has been decided on, the decision to invest in EOR or not *must* be taken. In this sub section we therefore assume that the decision to invest in capture plant has taken place.

Figure 19 illustrates some of the results from the analysis related to the EOR investment decision. The blue spots in a diagram represent the price combinations where the optimal decision is to wait (store the CO_2) in the specified year. The orange spots are the price combinations where it is more profitable to invest in EOR. The blue and orange spots together represent the total amount of possible combinations of prices in that time period.

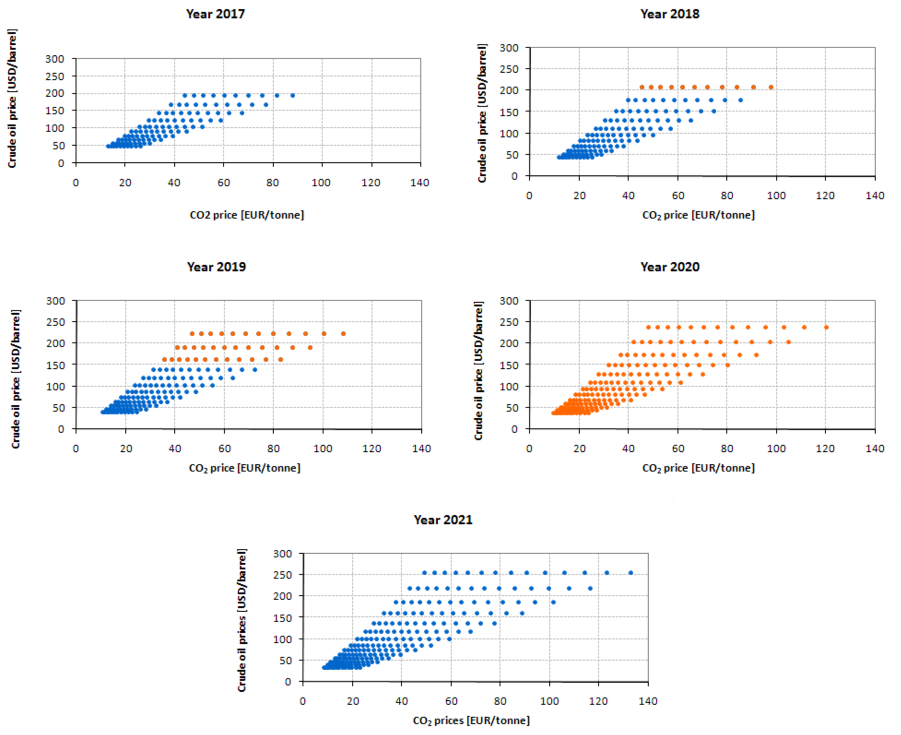


Figure 19: *Crude oil and carbon prices related to EOR investment*

As noticed in the previous section, investment in capture plant will not be profitable before 2014. Because of the three year investment period, the next decision does not take place before three years after the capture plant decision is made. If the investment in capture plant takes place in one of the years from 2014 through 2016 (which is only in very few price combinations, as observed in section 6.5.1) the results give that waiting is the dominating choice for the first year of capture, followed by EOR in later years. If the investment in capture plant takes place in 2017 or 2018 the dominating choice is to start EOR as soon as possible.

If the decision to invest in capture plant takes place after 2018, the EOR option is no longer available. Storage is therefore the only possible decision for these investment paths. As explained in section 6.5.1, this will only be the situation if the carbon and crude oil prices reach extremely high levels.

The decision rules, for whether to invest in capture plant or to wait, are given in Table 6. The rules are only given for years when the EOR option is available.

	Invest if:		Wait if:	
Year	**CO2 price [EUR/tonne]**	**Crude oil price [USD/barrel]**	**CO2 price [EUR/tonne]**	**Crude oil price [USD/barrel]**
2013-2017	Never	Never	Always	Always
2018	$> 45{,}5$	> 208	$< 45{,}5$	< 208
2019	$> 35{,}7$	> 163	$< 35{,}7$	< 163
2020	$> 9{,}50$	> 37.1	$< 9{,}50$	< 37.1

Table 6: *Decision rules, EOR investment*

6.5.3 Main findings for investment decision rules

The remarks given in the previous sections give some general trends:

- A general observation is that in all other years but 2018 it will never be optimal to decide to invest in capture plant as long as the carbon price is lower than 51.6 EUR/tonne and the crude oil price is lower than 143 USD/barrel. In 2018 the lowest prices for deciding to invest are 15.5 EUR/tonne CO_2 and 51.5 USD/barrel crude oil.

- Criteria concerning price levels change considerably when moving from year 2017 to 2018. Capture investments are carried out at much lower prices. This can be explained by the fact that in 2018 it is no longer possible to "wait" and also have the chance to invest in EOR. Investing in this period is therefore the only chance to start EOR. In the years before 2018 it is more profitable to wait than to invest in most of the price combinations.

- Storing CO_2 without EOR seems to be favorable only if the carbon prices and crude oil prices rise to high levels (82.7 EUR/tonne and 163 USD/barrel respectively[19]).

- When the CO_2 can be used for EOR, investment in capture plant is more profitable.

- It is not profitable to start injecting CO_2 for EOR before 2020, independently of the prices. In practice, this means that with the present price

---

[19] Numbers from capture investment decision in 2019.

forecasts and input data, the time interval for which the investment decision is optimal is only of three years, which is considerably smaller than the allowed time window of seven years.

- If capture investment decision is made as early as in the interval 2014-2016, at the majority of prices it is chosen to wait (operate storage) in the following year. When capture investment decisions are made in year 2017 and 2018, the follow-up decision is for most prices that of investing in EOR right away.
- The timing of the activities seems to be more dependent on the present year than on the actual prices.
- After 2026, if no project is chosen so far, it is for most price combinations prefered to pay quotas rather than starting capture.

6.6 Simulation results

In this section analysis is based on Monte Carlo simulation. When doing simulations the results may turn out different even though the base case is the same. All the input data are set, but the stochastic parameters have different outcomes in the various simulations. This section is an attempt of trying to visualize what the future may look like, and what the consequences will be concerning decisions. The results should be in accordance with the results derived from the stochastic dynamic model, described in section 6.5. Through simulations it becomes more apparent which prices that are more probable, and thereby which decisions that are to be more frequent.

In 98.9% of the simulations it is optimal to invest in capture. In all these cases it is also optimal to include EOR. In this section the spread in the decisions concerning the investment timing is analyzed, and the decisions are explained in the light of the price path of the simulation in question.

6.6.1 Distribution of timing for capture investment decisions

The timing for capture is highly concentrated. As much as 98.7 % of the capture decisions take place in year 2018. There is a small number of occurrences in year 2014, 2015, 2016 and 2017. Figure 20 shows the distribution of capture investments over these years. In time to reach the EOR time window, the investment decision of capture has to be made in 2018 at the latest. In the simulations, capture decisions are not made *before* 2014 or *after* 2018. This means EOR is always an option after finishing the investment years of capture.

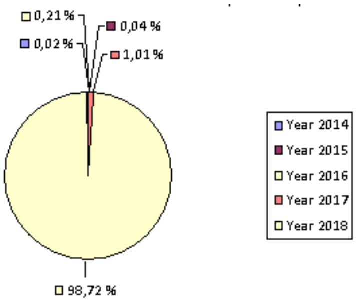


Figure 20: *Distribution of capture investment decisions over the years*

6.6.2 Distribution of timing for EOR investment decisions

In 99.2% of the simulations where investment is the optimal strategy, the best EOR investment decision year is 2020, making the distribution of the EOR decision even more concentrated than for capture. In a few simulations year 2018 or 2019 are better. Figure 21 shows the distribution of EOR investment decision over the the years. The simulations show that the EOR decision is preferably delayed as long as possible, until the end of the time window (2020).

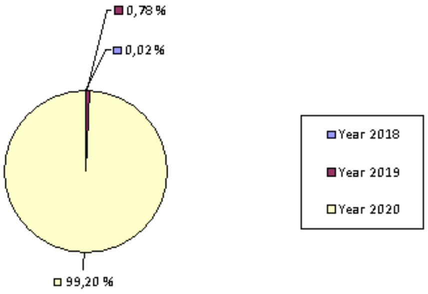


Figure 21: *Distribution of EOR investment decisions over the years*

Two ways of entering EOR

There are two paths of entering EOR operation, which boils down to the choice between the sequences *capture - EOR* and *capture - storage - EOR*. The first sequence is strongly dominating, constituting 99.8% of the EOR investments. Going straight from capture investment to EOR investment is the most typical procedure for ending up with EOR. A three year process of capture investment is started, and in the third year the EOR investment is carried out simultaneously, to be able to start EOR operation at the same time as capture the proceeding year. In practice this means that as soon as the CO_2 is sent through pipelines from Tjeldbergodden, it is used for EOR at the Heidrun platform, and the storage site stays vacant for a couple of years until the produced gas at Heidrun contains too much CO_2.

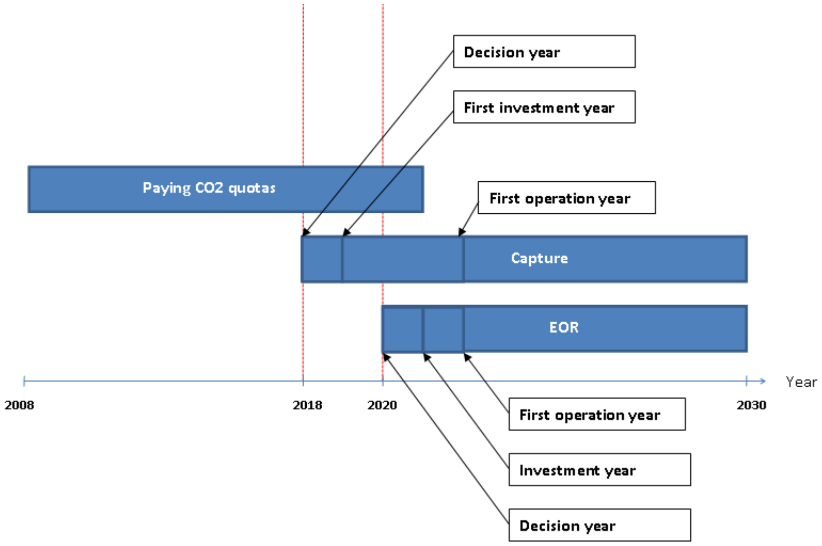


Figure 22: *Main investment path*

6.6.3 The main investment path

The dominating trends described in sections 6.6.1 and 6.6.2 lead to a pattern that from here on will be called the *main investment path*. This will be referred to in the proceeding text, and is illustrated in Figure 22.

The capture investment decision of the main investment path is carried out in 2018, being the most frequent year. Since the dominating year of EOR investment decisions is 2020, and the sequence optimal for the vast majority is that of *capture - EOR*, this will be the second part of the path. When looking at all the 50 000 simulations, 97.7% follow the main investment path. Note that capture is carried out as late as possible to still have the opportunity of implementing EOR. A sample price path for which the main investment path is implemented, is shown in Figure 23. The red line to the left represents the point of capture investment decision, whereas the line to the right represents the point of the EOR investment decision. The prices seem to be close to the forecast price, and they do not deviate much over time from the start price. Both oil and CO_2 prices at these points are above the price requirements for investment decisions for the years in question - refer to section 6.5. Prices and related investment decisions will be further commented later in this section.

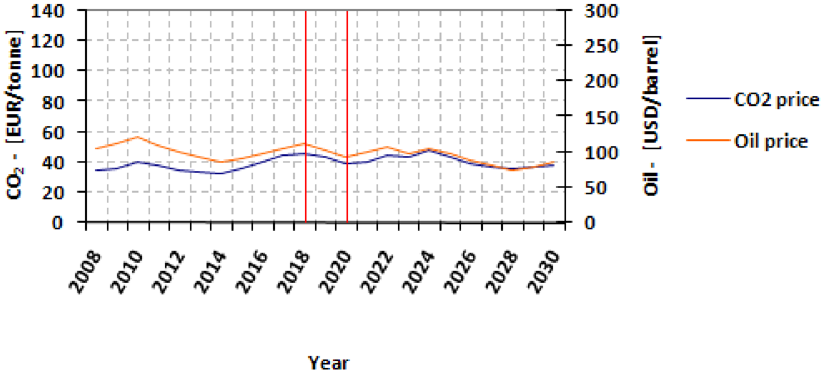


Figure 23: *A price path sample causing the main investment path*

6.6.4 Deviations from the main investment path

The remaining 0.28% of the 50 000 simulations take on slightly different routes than the main investment path. For all of them, capture *earlier* than what is typical is optimal (in some cases earlier EOR as well). The reason why different results are derived from the various simulations must be because the stochastic carbon and oil price take on different developments as time passes. All input data except the prices is equal for each simulation.

It must be commented that drawing conclusions from such a small number of simulations should not be done. The observations from this subset are anyhow presented to give a general impression, and to illustrate how extreme the price paths would have to be to make the investments deviate from the main investment path.

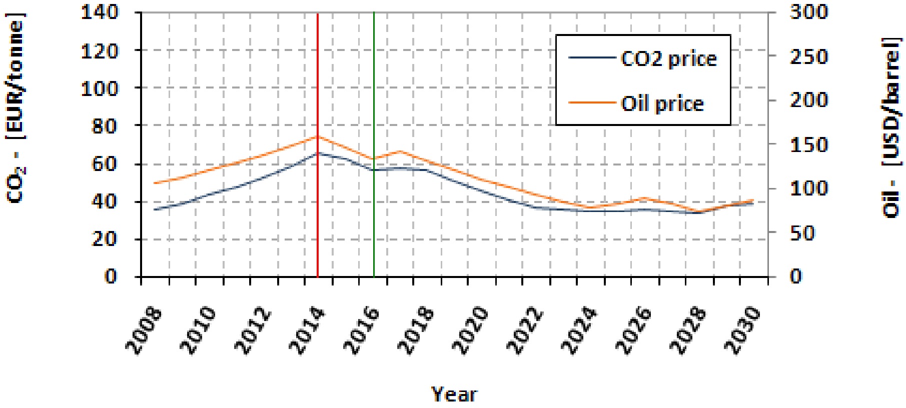
Early capture decisions combined with storage

What is triggering the decision of implementing storage in between capture and EOR? Cases will here be looked at where capture is carried out earlier than 2018, and storage is operated for a while before EOR is invested in. It is chosen to wait rather than investing in EOR right away. The simulations showed that, in such a case, storage is operated for one, two or three years before EOR is started.

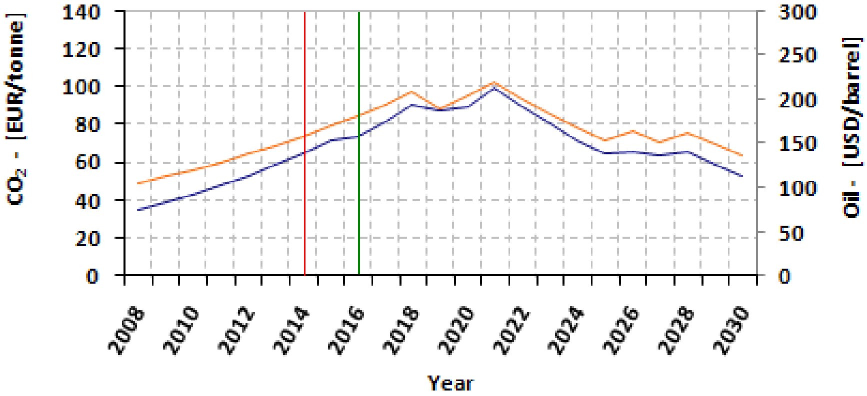
Figure 24 shows examples of price paths for which the optimal strategy would be to decide on investing in capture in year 2014, and then doing storage for some time. What is of interest here is the specific prices valid for the year when the capture decisions are made. From a specific price node, the future expected profit is calculated. If the price point implies a high CO_2 price, there is a potential for bright futures concerning the possible quota savings related to capture. A corresponding high oil price is also promising in the sense that revenues from possible EOR will turn out high. Such a foresight results in a high expected NPV. The decision needs to be made upon waiting - delaying the investment decision for an even brighter future - or going for capture at this point.

In the graphs the capture investment decision points are indicated by red lines. It is noticeable that at these points there are price peaks in the CO_2 and the oil prices (both peak since they are highly correlated). Looking firstly at the CO_2 price, a high value triggers the capture decision, meaning that we would rather avoid paying expensive CO_2 quotas. Note that the CO_2 price needs to reach a considerable level for this to happen, since the vast majority stick to the main investment path, regardless of the CO_2 price. The high oil prices at the investment decision points also join in triggering the capture investment, as the potential for possible future EOR revenues plays a role. Table 7 shows the CO_2 and oil prices of the capture investment decision years of the two examples. Both cases have identical prices. Figure 25 is taken from section 6.5 and shows the price points in which capture investment decisions are made and abandoned, for year 2014. The orange spot indicates the only price point of which capture investment is carried out. Both cases a) and b) of this section have in year 2014 prices identical to this spot. Their prices are marked by a red circle. This means that the prices are just high enough to make it favorable to invest in capture. This also confirms that the simulation results are in accordance with the direct results from the stochastic dynamic model.

Further, green lines are present in Figure 24, indicating a period of two years after the capture investment decision is made. This is when the choice comes up for the *first* time on whether to wait or to invest in EOR. The expected profit, standing in the certain prices of this year, is again evaluated. Since the prices are not satisfyingly high enough, standing in the given year, it is optimal to wait instead of going for EOR at these points. EOR investment limits concerning price points for this year, like those of Figure 25, can be found for these cases in section 6.5.



(a) Capture in year 2014, EOR in 2020



(b) Capture in 2014, EOR in 2019

Figure 24: *Early capture decisions combined with storage*

	Capture decision year	EOR decision year	CO$_2$ price at capture [EUR/tonne]	Oil price at capture [USD/barrel]
Case a)	2014	2020	65	158
Case b)	2014	2019	65	158

Table 7: *Prices in investment decision years for capture*

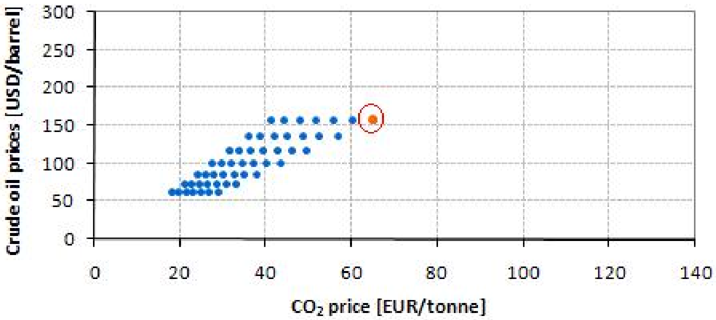


Figure 25: *Price combination points indicating capture investment decisions in year 2014*

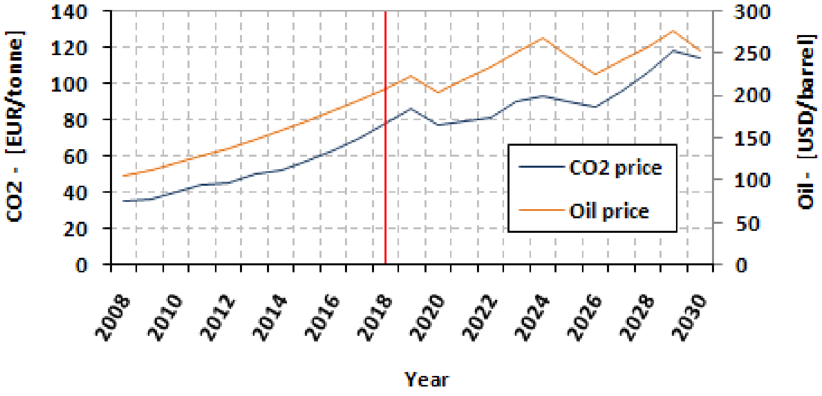
Early EOR decisions

In this section situations are analysed where the EOR decision is taken earlier than that of the main investment path, which means earlier than 2020. Capture and EOR are carried out right after each other, leaving no room for operating storage in between.

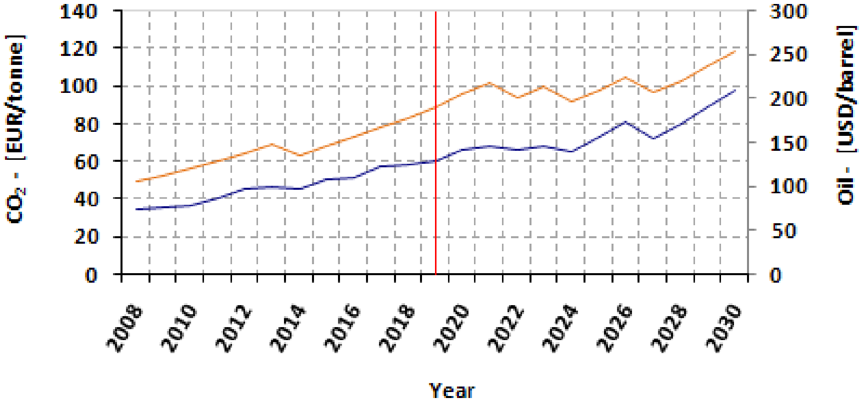
When EOR is invested in earlier than year 2020, particular conditions must apply. Capture is already decided on, earlier than average, meaning that the CO_2 and/or oil price at this point must have been higher than normal. Instead of waiting (i.e. going for storage) it is here chosen to go for EOR at an early point. What triggers this decision?

Figure 26 gives two cases where EOR is decided on already in year 2018 (case a) and in year 2019 (case b). The decision years are marked by a red lines. It should be kept in mind that, as capture is already initiated, the CO_2 price no longer plays a role in the decision making, since quotas are already avoided for the rest of the time period. What matters now is the potential revenues from EOR, represented by the oil price. For both cases in the figure the oil price reaches a considerably high level in the EOR decision year. Table 8 contains the specific values.

The high oil prices, implying high expected NPVs, trigger the EOR investment to take place earlier, like for the two cases of EOR in 2018 and 2019. It should anyhow be pointed out that only in a very small percentage (<0.28 %) of the instances the oil price is high enough for advancing the EOR decision to the years before 2020. Figure 27 is taken from section 6.5, and is valid for EOR decisions in year 2018 and 2019. The price points from case a) and b) of this section are circled out. They are situated in areas where EOR implementation is favorable.



(a) Investment in EOR in 2018

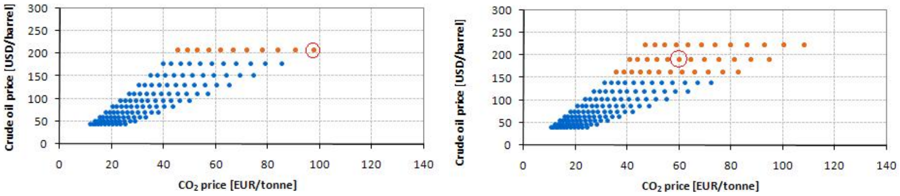


(b) Investment in EOR in 2019

Figure 26: *Early EOR decisions*

	EOR decision in year	Oil price [USD/barrel]
Case a)	2018	208
Case b)	2019	191

Table 8: *Prices for early EOR investments*



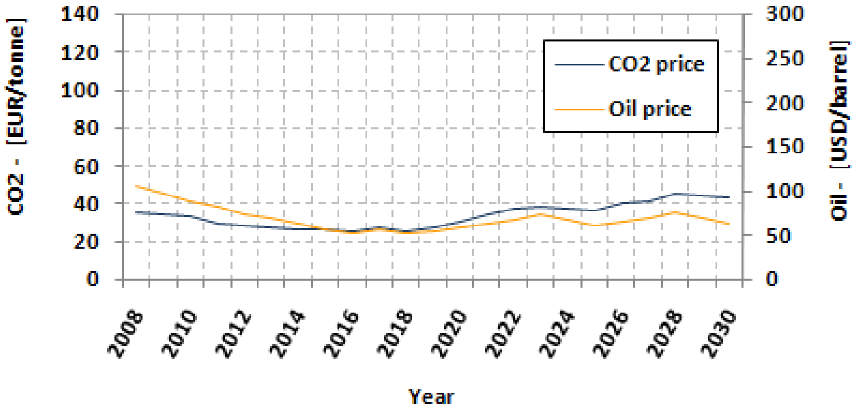
(a) Year 2018

(b) Year 2019

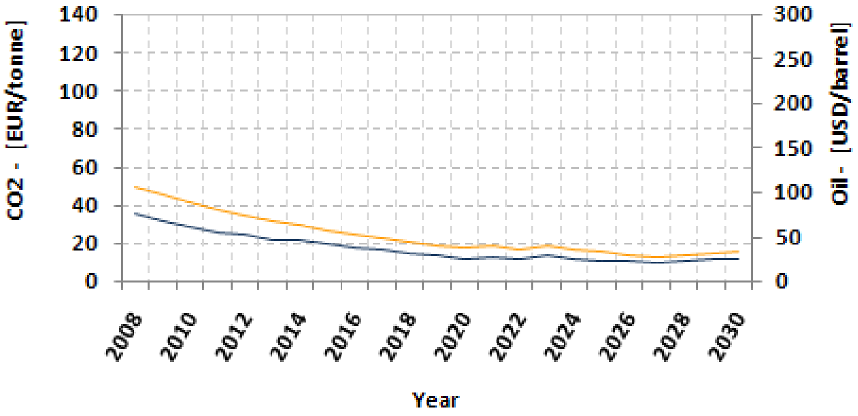
Figure 27: *Price limits for EOR investment decisions in year 2018 and 2019*

6.6.5 Cases of no investments

In 1.1% of the simulations the optimal strategy was to not invest. The NPVs of these are in the interval from -1 120 mill EUR to -627 mill EUR. The price paths resulting in the highest and lowest NPV are shown in Figure 28. Both paths are rather unfavorable as they decrease from start. The prices for the typical investment year for EOR (year 2020) is shown in Table 9. They have sunken to respectively 59.0 and 37.0 USD/barrel, which is contributing in the decision of not investing. Low oil price represents low EOR revenues, together with low opportunity cost of CO_2 quotas. It is more beneficial to buy quotas rather than investing a considerable amount in the value chain, where small revenues are expected.



(a) Lowest NPV: -1120 mill EUR



(b) Highest NPV: -627 mill EUR

Figure 28: *Price paths for cases of no investments*

	Oil price [USD/barrel] in year 2020
Case a)	59.0
Case b)	37.0

Table 9: *Prices for the typical EOR decision year*

6.6.6 Distribution of NPVs from simulations

We want to see the effect the uncertainty in prices has on the profitability of the value chain. The distribution of the 50 000 NPVs gives an indication of how uncertain (how fluctuating) the profitability of the project is due to changing price paths. Figure 29 shows the frequency of simulations with NPVs within intervals of 311 mill EUR[20] (2 500 MNOK). Because of the high spread of the frequencies in different intervals and the low frequency in some of the intervals, the least represented intervals are not visible in the diagram. All the intervals in the diagram are still represented by at least one simulation. The difference between the lowest and highest NPV is therefore at least 5 210 mill EUR (4 050 + 1 250 mill EUR). The NPVs are clearly centered in a smaller interval than this. To have a closer look at the most represented interval, the range of values are divided into smaller intervals.

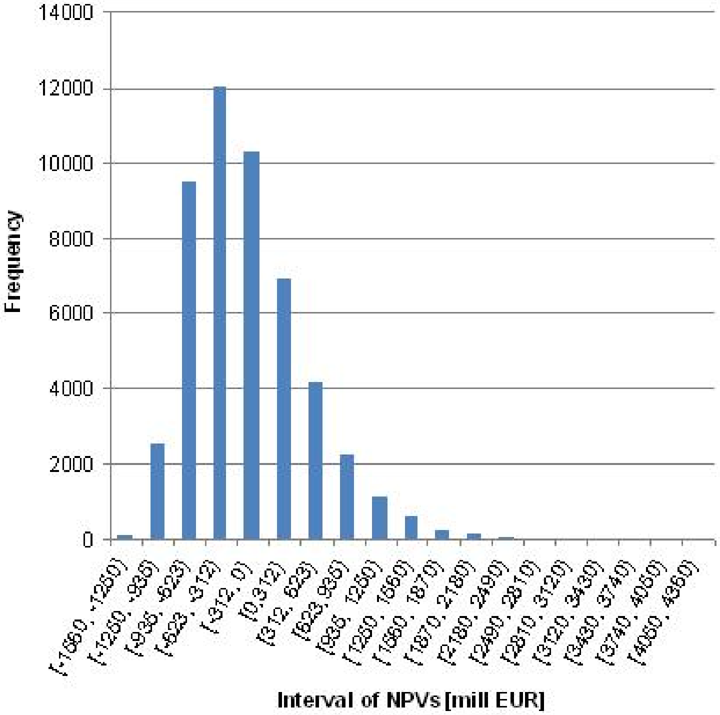


Figure 29: *Distribution of the NPVs from simulations (I)*

With intervals of 62.3 mill EUR (500 MNOK), 90% of the simulations are included in intervals where the frequency is higher than one percentage of the total amount of simulations. Figure 30 gives the same information as Figure 29, only with the new intervals of 62.3 mill EUR. We observe that the difference between the lowest and highest NPV has now decreased to 1 600 mill EUR.

---

[20] the rounding of the values results in the intervals looking different in size

The highest frequency is in the interval [-499, -436), considerably lower than the value of the real option (- 191 mill EUR). As the results seem to be log normally distributed, the mean of the NPVs is outside of this interval and higher. The mean of the NPVs is calculated to be -194 mill EUR, which is close to the value of the real option.

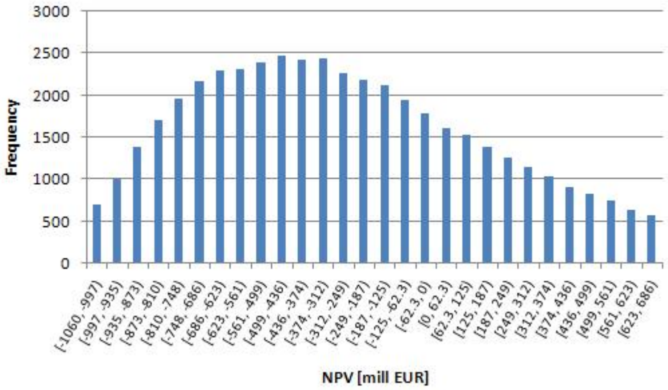


Figure 30: *Distribution of the NPVs from simulation (II)*

6.6.7 Main findings from simulation analysis

- A main investment path was discovered through simulations, since 97.7% of the simulations ended up in this route. This path consists of waiting until 2017, deciding for capture investment in 2018, and deciding for EOR investment in 2020.
- Other results concerning prices and investment decisions all confirmed what was found in section 6.5:
  - Capture is not carried out without EOR
  - Early, considerable CO_2 and oil prices may in very few cases advance the capture and EOR investment decision
  - Generally low prices up to year 2020 end up in no investments, since it becomes more favorable to buy quotas than carrying the investments and operating costs of capture, storage and EOR

6.7 Sensitivity analysis

In this sub-section the results of sensitivity analysis are presented. Most of sensitivity data used is found in Appendix E. The focus area is the sensitivity of the investment timing decisions to changes in selected parameters. Some parts of the analysis are based on changes in the real option value, whereas other are based on Monte Carlo (MC) simulations. Changes in the timing decision are exclusively taken from the Monte Carlo simulations. We might as well have chosen to base the entire analyses on the results from the stochastic dynamic program, which should lead us to the same conclusions, given that the number for MC simulations is sufficiently high for the model to give reliable results. According to the conclusion of the validity test in section 6.2, 50 000 is sufficient. Hence, when referring to simulations in this sub-section, 50 000 simulations are applied.

In this section *the main (investment) path of the base case* refers to the investment path that is proven to be dominating for the base case and that is presented in (simulations).

For the sensitivity to carbon price forecasts and crude oil price forecasts in sections it is important to keep in mind that the price forecasts merely form the basis for the stochastic price developments in the non-rectangular tree which was explained in section 5.2.1. Hence, a constant price forecast does not imply constant prices, but that the slope of the forecast will be zero going forward.

6.7.1 Sensitivity to carbon price parameters

The sensitivity to the carbon price volatility and the expected future carbon price is analysed in this section. For the expected future price, two alternative forecasts found in the IPCC fourth assessment report are implemented in addition to other levels of constant forecasts.

Volatility

Figure 31 shows how the value of the real option varies as a function of the volatility when the volatility is within the interval $[0, 1]$ (based on discrete changes in the volatility). It indicates that within the volatility interval 0-0.15 the uncertainty does not have a significant impact on the value of the real option. The volatility of 0.0775 applied in this thesis is well within this interval.

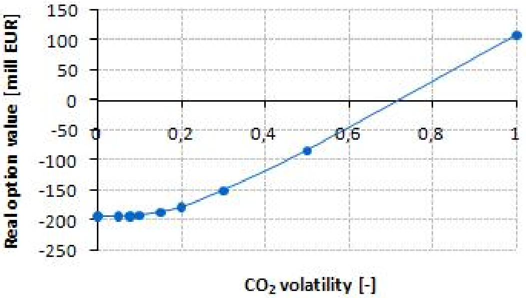


Figure 31: *The real option value at different carbon price volatilities*

Figure 32 shows the investment rate and the rate of changed investment paths from the main path for the same discrete volatilites. As long as the volatility is below 0.15 the main investment path from the base case is strongly dominant. The investment rate is also stable for volatilities below 0.15, and is never less than 94% for the tested interval. The investment timing is therefore not sensitive to small changes in this parameter. Within our model, the volatility may be twice as high as the value we have used, before its change will be reflected by the timing decisions.

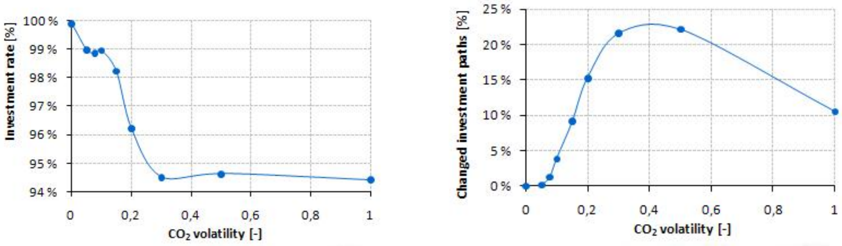


Figure 32: *The investment rate and the rate of changed investment paths at different carbon price volatilities*

When the volatility is higher than 0.15, the graph in Figure 31 shows that the value of the real option increases proportionally with the volatility. This means that the upside for the value of the real option in case of increased volatility is higher than the downside.

We have not analysed the sensitivity of the volatility for values above 1 because it is far away from the value applied in this thesis.

IPCC price forecasts

As two extreme scenarios, we use forecasts found in the IPCC fourth assessment report [IPCC 2007][21]. IPCC refers to modeling studies, consistent with stabilization at 550 ppm CO_2equivalents by 2100, that show carbon prices that rise to levels between 14.6 and 58.4 EUR/tonne[22] by 2030. By using the observed carbon price from the start of 2008[23] and constant slope until 2030, the two extreme points of these modeling studies give us two new price forecasts, one decreasing and one increasing. The EUR-values of these forecast are presented in Table 10.

Price forecast	Forecast development	2008 price [EUR/tonne CO_2]	2030 price [EUR/tonne CO_2]	Value of the real option [mill EUR]
Base case	Constant	35.0	35.0	-191
IPCC	Decreasing	23.0	14.6	150
IPCC	Increasing	23.0	58.4	-73.2

Table 10: *The real option value with IPCC forecasts*

For the decreasing forecast, the investment rate decreases very slightly and the main investment path from the base case is very strongly dominant. The timing is therefore to a very large extent unaffected by the carbon price decline. The value of the real option is 150 mill EUR. This value is better than in the base case because the carbon prices are here lower, and thus that the cost of paying quotas for the same number of years, has been reduced by approximately 340 mill EUR.

When the increasing IPCC price forecast is used, corresponding trends are observed. The main investment path from the base case is still very strongly dominant. A very low number of simulations at high price outcomes are optimal with investment starting a few years earlier because quota cost avoidance encourages earlier capture. The number of simulations without investment is negligibly small. The value of the real option for this forecast is -73.2 mill EUR. The fact that it is better than for the base case is that the CO_2 prices in the beginning of the time horizon (2008-2017) are lower for the increasing IPPC forecast than for the base case forecast.

Constant carbon price forecasts

The level of the (constant) price forecast is changed discretely from 0 to 62.3 EUR/tonne[24] CO_2 to see the sensitivity on the investment results. A nearly

---

[21] Working Group III Report "Mitigation of Climate Change", Summary for policy makers, p. 19

[22] Originally 20 to 80 USD/tonne (2006)

[23] The carbon price on January 2nd 2008 was 23.0 EUR (www.pointcarbon.com)

[24] 500 NOK/tonne

linear decline of the real option value as a function of the carbon price forecast value is observed, as indicated in Figure 33. Figure 34 shows the investment rate and the rate of changed investment paths from the main path at the different constant forecasts. The investment rate is close to unaffected by the changed price forecasts. The investment pattern is however to some degree sensitive to the carbon price. When the price forecast is high, other investment paths become more frequent. The simulations imply that the capture investment is carried out some years earlier as compared to the base case. The EOR investment timing does however not change; it will in all cases start in 2022. The CO_2 captured before EOR starts is directed to the Alpha structure for permanent storage. This observation is explained by the incentive high carbon prices create for avoiding emissions; it is so expensive to emit CO_2 that it is favorable to invest in capture facilities and start capturing earlier.

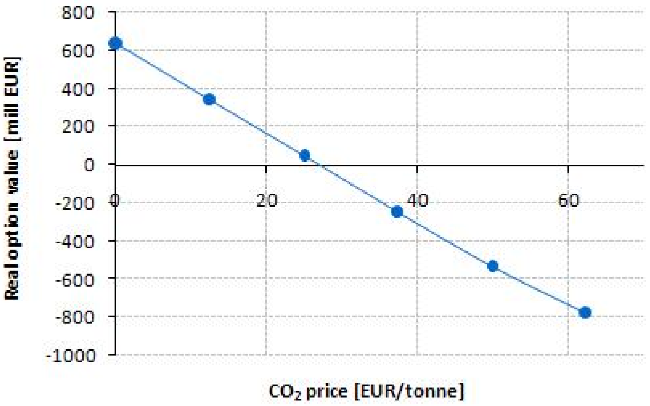


Figure 33: *The real option value at different constant carbon price forecasts*

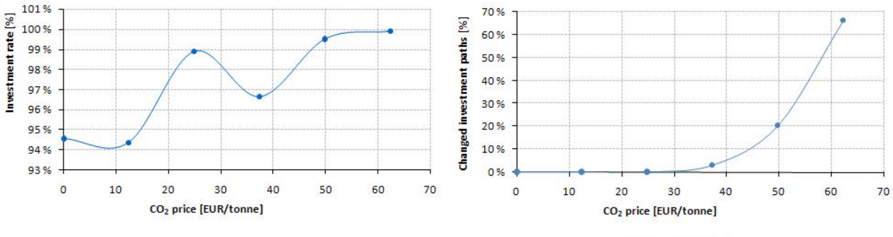


Figure 34: *The investment rate and the rate of changed investment paths at different constant carbon price forecasts*

It is noteworthy that the investment rate seems to be close to unaffected by the level of the carbon prices. The case where the price on carbon emissions is zero should emphasize this fact; investment is preferred when the cost of emitting is very small. Hence, it may seem like there are other drivers than the carbon price which are critical to the the investment timing or at least to the “invest or not” decisions.

6.7.2 Sensitivity to crude oil parameters

The sensitivity to crude oil price volatility and price forecasts are analysed in this section.

Volatility

The impact of discrete changes in the volatility within the interval $[0, 1]$ is explored for the real option value and the investment timing. In Figure 35 the real option value is illustrated as a function of the volatility. In the interval 0-0.1 the real option value is rather stable with regards to uncertainty. The volatility of 0.0775 applied in this thesis is within the upper part of this stable interval. Hence, if the volatility increases, the real option value may be affected. Figure 36 shows the investment rate and the rate of changed investment paths from the main path as functions of the crude oil volatility. The investment rate is rather unaffected by changes in the uncertainty and the main investment path from the base case is very strongly dominant as long as the volatility is below 0.12.

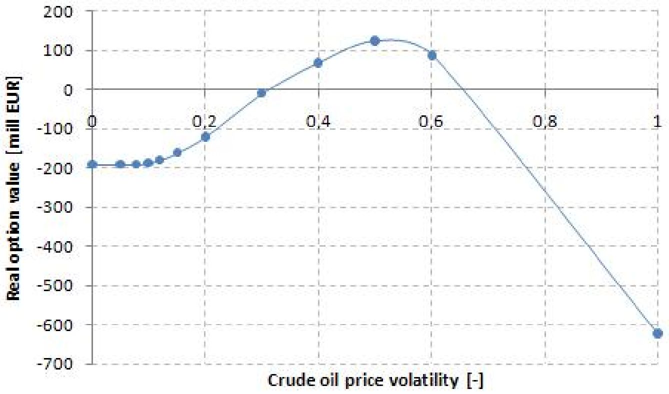


Figure 35: *The real option value at different crude oil price volatilities*

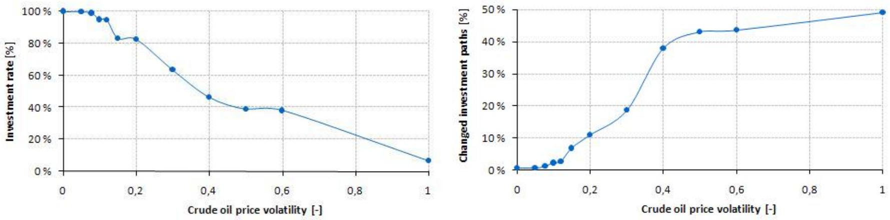


Figure 36: *The investment rate and the rate of changed investment paths at different crude oil price volatilities*

When the volatility is smaller than approximately 0.5, the real option value increases when the volatility increases. The opposite trend is observed for volatility above this value. This phenomenon may be explained by the impact the uncertainty of oil prices has on the investment pattern within different intervals of the volatility, which we will explain in the following.

For volatilities above 0.12 the investment rate decreases as the volatility increases. The volatility may therefore increase by more than 50 % from the base case value before the investment rate will be affected.

From about 0.3 the simulations indicate that it is increasingly more likely not to invest than to invest. As the uncertainty increases, the price spread for each period in the non-rectangular tree becomes wider. In other words, the nodes in the tree with high oil prices have higher values as the uncertainty increases. This opens for increasing the extra oil revenue potential. The opposite is however also true; if low oil prices occur, the revenue potential decreases as the uncertainty increases. At about 0.3 the low income possibly obtained dominates the high income possibly obtained, so that it becomes relatively better to pay carbon quotas than investing and running the risk of low extra oil revenue. In the upper range of the uncertainty interval, the risk of low extra oil revenue is so high that it is gradually better to renounce the opportunity for high income and undertake the carbon emission costs.

The real option value increases until the volatility is approximately 0.5 reflecting the expected NPV of a combination of price developments with very high income or no investment at all. After 0.5 it decreases as emissions with the quota costs become increasingly more favorable than capturing the CO_2.

Price forecasts

The base case is, as explained in section 5.4.5, derived from a decreasing forecast starting in 105 USD/barrel and ending in 88.8 USD/barrel in 2030. The sensitivity of the model to crude oil prices is examined by replacing the base case forecast with constant forecasts within the interval from 15.8 to 158 USD/barrel[25]. Figure 37 shows the investment rate as a function of the crude oil price. It clearly shows that capture investment is not implemented when oil price forecasts are low. This may be explained by the fact that at low oil prices the revenues of EOR will not exceed the required investments. At a constant forecast price between 40 and 50 USD/barrel, the rate of investment exceeds the rate of not investing. At lower prices, waiting is the most likely choice. In the region of 80 EUR and upwards, the investment rate is higher than 95 %. The choice between investing in capture or not is significantly sensitive to oil prices, whereas the timing decisions for investments, illustrated in the same figure, prove to be less sensitive to the oil prices. This observation indicates that the optimal EOR timing is independent of the oil price, and that EOR as late as possible is most favorable. It should be remarked that throughout this part of the sensitivity analysis there are no occurrences of capture investments without EOR.

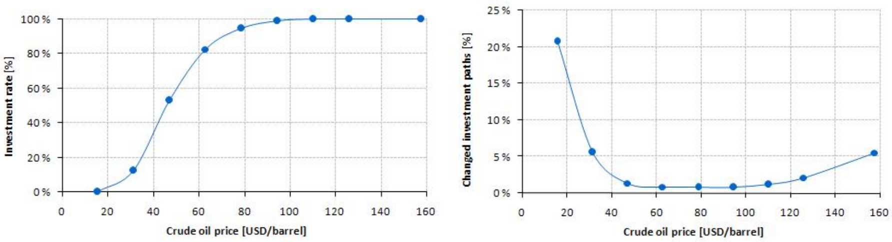


Figure 37: *Development of the investment rate with varying constant oil price forecasts*

The real option value for the different levels of constant crude oil price forecasts is shown in Figure 38.

---

[25] 10 - 100 EUR/barrel

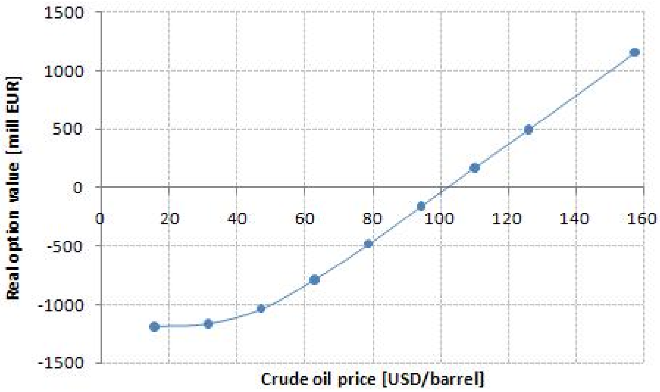


Figure 38: *The real option value at different constant crude oil price forecasts*

6.7.3 Sensitivity to the correlation factor

For the carbon and crude oil prices, the correlation factor $\rho_{oc} = 0,87$ is used in the base case, expressing a considerable degree of linear dependence between the parameters. The rational behind the factor used is in section 5.4.5. Discrete changes in the correlation factor within the interval $[0, 1]$ are implemented to explore the impact for the real option value and the investment timing. It is assumed that the price correlation between the two prices is solely positive. The investment rate and the changes in timing at different correlation factors are shown in Figure 39. The main investment path from the base case is very strongly dominant for all price correlations within the interval and the investment rate is nearly unaffected. These results indicate that the timing is unaffected by the changes in correlation factor. The real option value is shown in Figure 40. It is only slightly affected by the changes, $\rho_{oc} = 0$ gives a real option value of -192 mill EUR and $\rho_{oc} = 1$ gives a real option value of -191 mill EUR.

Negative correaltion between the two commodity prices is very unlikely, unless policy makers force the carbon price in a specific direction. We did however examine the impact on the timing of negative correlation, and it proved to be insignificant.

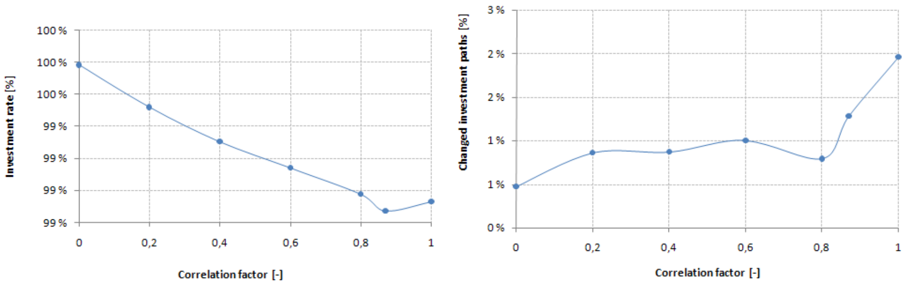


Figure 39: *The investment rate and the rate of changed investment paths at different correlation factors*

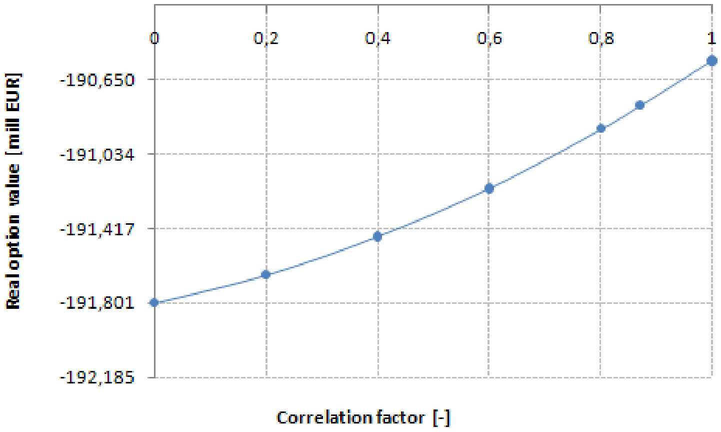


Figure 40: *The real option value at different correlation factors*

6.7.4 Sensitivity to the discount rate

The discount rate is set to 5.5 % in the base case, see section 5.4.6. Because this is lower than what have been used in other studies, it is of interest to see if small changes in this value affect the investment timing. By changing the discount rate by discrete amounts from 5% to 8% we see that only the value of the real option differs. Figure 41, giving changes in timing and investment rate at different discount rates, indicates that the investment timing is unaffected by changes within this interval. This is based on the fact that the main investment path from the base case is very strongly dominating for all rates and that the investment rate hardly changes. As a basis for comparison with other studies, the changes in the real option value, as a consequence of changes in the discount rate, is given in Figure 42.

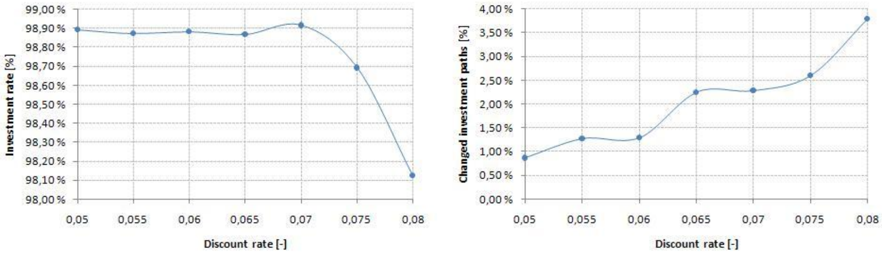


Figure 41: *The investment rate and the rate of changed investment paths at different discount rates*

Figure 42: *The real option value at different discount rates*

6.7.5 Sensitivity to selected cost parameters

The sensitivity to the deterministic cost parameters that are seen as the most uncertain, are analysed in this section. The chosen parameters are those investment and operating costs related to new or not proven technology. Sensitivity to cost parameters related to proven technology as pipelines and injection wells are not studied.

Sensitivity to investment costs for capture and separation

It should be noted that the investment costs for capture and separation both in the base case and in the sensitivity analysis are time dependent due to assumed cost reduction, as explained in section 5.4.3. In order to analyse the sensitivity of the results to changes in the investment costs for capture and separation, we change the start value of the cost to the levels ranging from 60 % to the 120 % of the base case level. The impact of the changes prove to be negligible on both investment rate and timing decisions. This is illustrated in Figure 43. The main investment path from the base case is very strongly dominant for all studied levels. The value of the real option will obviously change according to the cost change. This is shown in Figure 44.

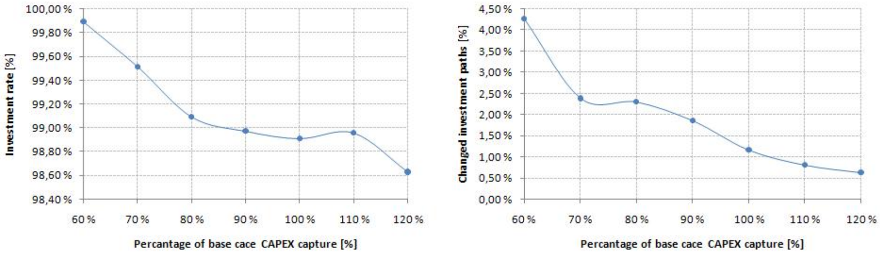


Figure 43: *The investment rate and the rate of changed investment paths at different capture plant investment costs*

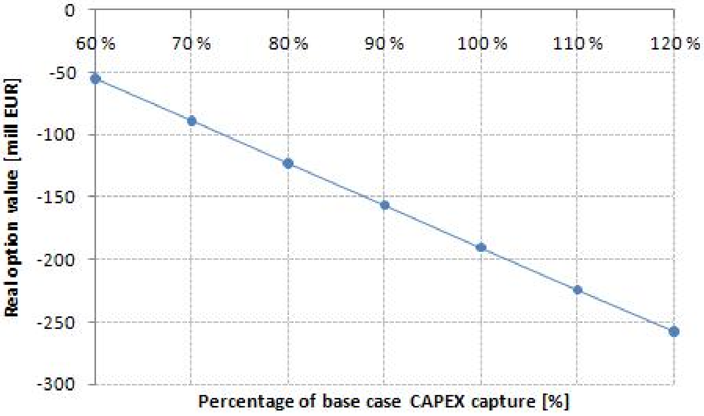


Figure 44: *The real option value at different capture plant investment costs*

Almost the same conclusion as above may be drawn from a case where the capture and separation costs are held constant (instead of gradually decreasing from 2010-2020), at the same level as the start level of the base case. The results show a small increase in the rate of investment paths that are different from the main path of the base case. The main investment path from the base case goes from being very strongly dominant to strongly dominant. Other observations are that the value of the real option increases from 191 mill EUR to 485 mill EUR and the investment rate decreases from 98.9% to 94.0%.

Sensitivity to operating costs for storage

Figure 45 illustrate the change in investment rate and timing decision when the operating costs for storage are changed to discrete values varying within the interval of 0-200 % of the corresponding base case cost. No considerable investment rate or timing decision impacts are observed. The main investment path from the base case is very strongly dominant for all studied values. The value of the real option is thereby diminishingly sensitive to this parameter, and is shown in Figure 46.

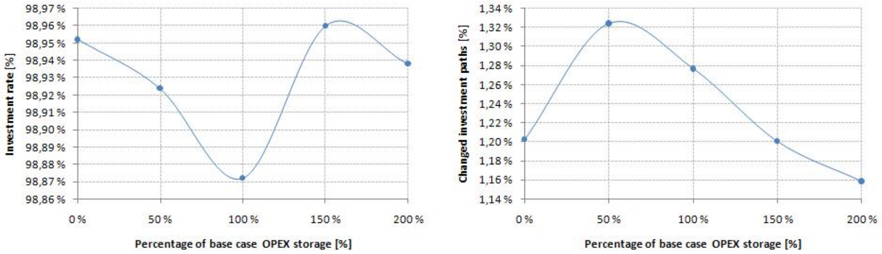


Figure 45: *The investment rate and the rate of changed investment paths at different storage operating costs*

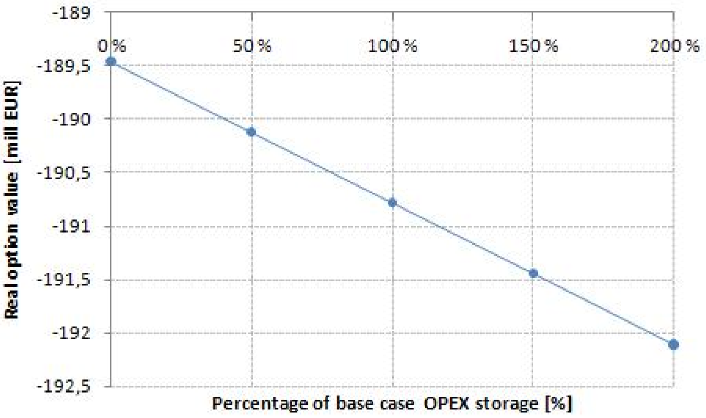


Figure 46: *The real option value at different storage operating costs*

Sensitivity to operating costs for capture and separation

We examine whether changes in the operating costs for capture and separation plant affect the investment timing decision. We let the costs vary between 0 % and 200 % of the base case costs, i.e. from 0 to 150 mill EUR. Figure 47 shows the investment rate and the changes in timing decision from the main path as functions of the operating cost. It indicates that when the cost is higher than the base case cost, the investment rate will decrease as the cost increases. This trend is reflected in the real option value, which is shown in Figure 48. The real option value is very sensitive to the cost change. This implies that these costs constitute a significant part of the total costs, a fact we will come back to later in this sub-section.

The timing decisions also prove to be sensitive to the operating costs. The rate of investment paths which differ from the base case main path is shown as a function of the operating costs. The graph shows clearly that when the operating cost declines below the base case cost, the rate of timing decisions which differ from the base case main path increases.

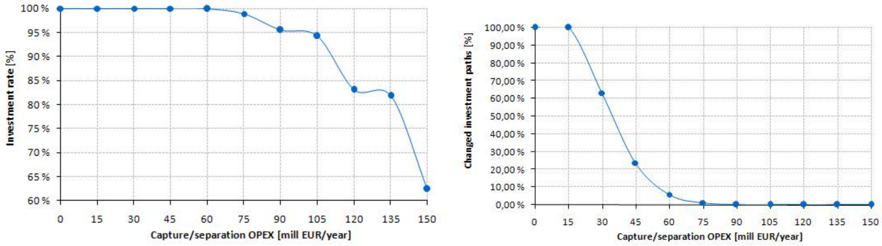


Figure 47: *The investment rate and the rate of changed investment paths at different capture plant operating costs*

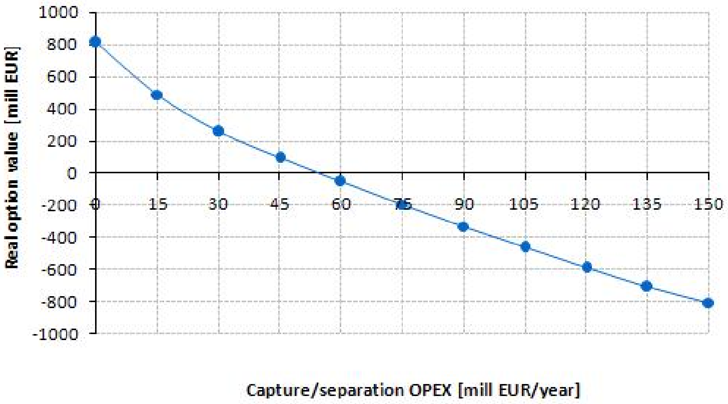


Figure 48: *The real option value at different capture plant operating costs*

The operating costs for capture and separation are respectively 74.8 mill EUR per year (before inflation), whereas the expected cost of emitting the CO_2 (if capturing is not installed) is 70 mill EUR a year (2 Mtonnes a year at 35 EUR/tonne). Hence, the yearly saving potential by including capture is consumed by the operating cost of capture alone. When investment costs for capture, pipelines and storage as well as the corresponding operating costs are added, it seems clear that CCS alone will not be profitable. This corresponds well with results from base case simulations and sensitivity analysis simulations which very close to never suggest capture without EOR. Hence, within the value chain of this thesis, it is the potential extra oil revenue from EOR which controls the timing.

6.7.6 Robustness

A model applicable for several conditions needs to be robust in order to avoid loosing its relevance. The sensitivity analysis proved that the model is relatively robust, since the decisions were not altered to a large extent as the input parameters were changed. This means that the conditions under which the value chain is evaluated, may change a lot, and the investment decisions and the timing of the activities will mainly be the same.

6.7.7 Main findings from sensitivity analysis

The most noteworthy results from the sensitivity analysis will be listed here. All the parameters for which the model proved insensitive will not be mentioned:

- If the carbon price volatility turns out to be more than the double of today, but no less, deviations from the main investment paths are more likely to be seen in the results. The same is true for changes in the real option value.
- Increased expected carbon price (up to 62.3 EUR/tonne[26]) will only affect the timing decisions by advancing the capture decision.
- As the oil price volatility increases to 0.12 the investment rate starts to decrease. The volatility has to rise significantly before the timing decision changes.
- Changing expected oil prices affect the investment rate significantly, going from no investments as the oil price is close to zero to more than 90% as the oil price is around 50 EUR/barrel and upwards. The timing decision is not sensitive to changing expected oil price, within the studied interval.
- The model results are not significantly sensitive to changes in the correlation factor.
- Only the value of the real option changes as the discount rate changes within the interval [5%, 8%].
- If the capture plant and separation plant investment costs turn out to stay constant (not halve before 2020) the value of the real option decreases considerably and the investment rate decreases slightly.
- Both the investment rate and the timing decision are sensitive to changes in the operating costs from capture and separation. As the operating costs decreases, new investment paths become optimal. As the operating costs increases, the investment rate decreases.

---

[26] 500 NOK/tonne

7 Discussion

Based on results presented in the previous section, we may conclude that one investment path is strongly dominating all others, given the input conditions and the selected method for price uncertainty implementation in crude oil and carbon prices. This main investment path includes the capture investment and the enhanced oil recovery (EOR) investment. The capture investment consists of investments in capture plant, storage facilities and pipelines. The EOR investment consists of investment in CO_2 injection facilities and separation facilities for CO_2 and natural gas. The timing of this main investment path is illustrated in Figure 49.

In the main investment path emission costs are paid from 2008-2021. In 2018 the capture investment decision is made, followed by three years of investment completion. The EOR investment decision is taken in 2020, followed by investment in 2021. In 2022 capture and CO_2 injection are initiated, followed by operation until the end of time horizon in 2030. Even though this is the timing which generally seems best now, the result mainly implies that it is better to postpone the decisions than to invest now. New information may be revealed as time passes, changing the economic and political conditions for the value chain. New analysis should be carried out later.

The first important conclusion we may draw is that for the majority of possible price paths it is better to invest in the value chain than not to. The second conclusion is that it is hardly ever profitable to invest in capture without EOR given all possible price paths in this thesis. Finally, and most importantly with respect to the purpose of this thesis, which is to evaluate timing decisions for the CO_2 value chain, the timing of both capture and EOR are optimal for a large majority of price paths as late as possible for EOR to be implemented. In the following sub-sections these results will be discussed and explained based on the analysis presented in the previous chapter.

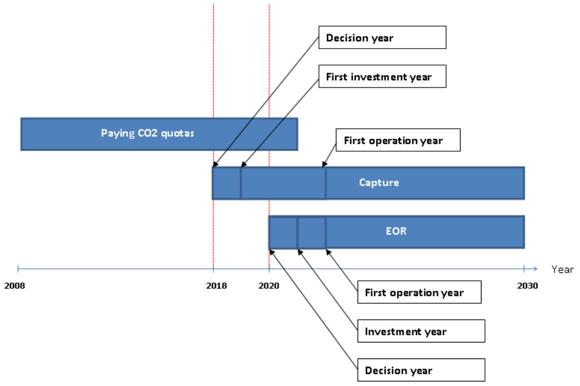


Figure 49: *The main investment path*

7.1 Profitability of the value chain

The results clearly tell that it is very probable that investing will be more profitable than not investing, or more accurately - less unprofitable than not investing. In this section we disregard timing and discuss how investments are triggered and what the investment rate actually is sensitive to.

There are three mutually exclusive investment combinations. These include *no investments* throughout the time horizon, *capture and storage investment only* and *capture and storage investment with EOR investment*. The three combinations and their associated cost and revenue components are shown in Table 11.

The analysis of the results has shown that the combination of capture and EOR investment is highly dominating with the given input data. We have also seen that the profit from this combination, for most of the possible future price paths, dominates the profit of not investing at all, which again dominates the pure capture and storage investments. Which investment combination that is optimal for each possible realisation of prices depends on the net contribution from investments compared to the costs of doing nothing (not investing). The net contribution from investing corresponds to the difference between the revenues and the costs following the investments. We will now take a closer look at each of the three investment combinations, starting out with the most frequent one.

Investment combination	**Cost components**	**Revenue components**
No investments	Carbon costs throughout the time horizon	-
Capture and storage investment only	Carbon costs until capture is installed, investment in and operation of capture, storage and pipelines	-
Capture and storage investment and EOR investments	Carbon quotas until capture is installed, investment in and operation of capture, EOR facilities, storage and pipelines	Extra oil revenues

Table 11: *Mutually exclusive investment combinations when timing is disregarded*

Capture and storage with EOR Capture and EOR investments are triggered in price paths that give that the net contribution from investing is better than the carbon costs from the first capture year and throughout the time horizon. This has been showed to be the situation for a majority of the possible price paths. The simulations carried out in section 6.6 indicated an investment rate of 98.9 %[27], all investments as combinations of capture and storage and EOR.

Not investing at all There are a few possible price paths where crude oil and carbon prices are so low that it is better to pay carbon costs throughout the time horizon and renounce the extra oil revenues, than to carry the investment and operating costs.[28] The net contribution from investing is then worse than the carbon costs.

Capture and storage only As for investing in capture and storage only, the net contribution from investing consists of the investment and operating costs for capture, storage facilities and pipelines. No revenues are generated. There exists a negligibly small number of price paths for which capture and storage alone is the optimal investment decision. This investment is triggered when the carbon prices are extremely high, an observation which was supported by the sensitivity analysis of carbon price forecasts.[29]

Which factors do actually influence the investment decisions? By examining the impact of the crude oil price on the result, it was shown that the oil price

---

[27] Based on 50 000 simulations. See section 6.6 for details

[28] See section 6.5 for details.

[29] See section 6.7 for details.

in 2008[30] should be lowered to below ca 45 USD/barrel (from the applied price of 105 USD/barrel) for the revenues from extra oil sales to be so low that not investing dominates investment decisions. For the deterministic input parameters, the sensitivity analysis showed that the model was sensitive to changes in the operating costs for capture and separation. Simulations indicated however that if these large, annually occurring costs double, the investment rate would decrease from 99% to 62%, meaning that investing still is the best choice for the majority of price paths, but that for a significant number of price paths it is not optimal to carry out investments at all.

The fact that the carbon and crude oil prices are strongly correlated, complicates the separation of those decisions which are triggered by oil prices, those which are triggered by carbon prices and those which are triggered by combinations of the two. The strong correlation factor of 87 %, implies that the two prices follow each other pretty closely. The sensitivity analysis did however prove that the investment decisions are not significantly sensitive to changes in the correlation factor. The sensitivity analysis for carbon prices indicated that even if carbon prices are diminishing, the EOR investment option will be very strongly dominating. In light of the impact of crude oil price and carbon price, this may imply that the carbon price is influencing less than the crude oil price. Even if there is no cost related to emitting CO_2, it is in most price paths favorable to capture and carry out EOR in order to obtain extra oil revenues. The incentive for capturing is mainly based on the extra oil revenue potential.

7.2 Timing decisions for the main investment path

We have now established that, taking the possible price developments for crude oil and carbon into account, it seems likely that it will be better to invest in the CO_2 value chain with EOR than to carry the carbon costs, or to invest in capture and storage without EOR. It is now relevant to discuss the investment timing which is the main focus of this thesis. For the purpose of evaluating investment timing decisions, it is no longer adequate to consider the three investment groups referred to earlier in this section. These groups are merely the combinations of the projects which are undertaken and the projects which are not, independently of timing. We will now discuss how the two investment projects are optimally scheduled and how the investment decisions affect each other.

The capture plant investment project[31] is evaluated annually from the first year throughout the time horizon or until it is undertaken. The decision basis is the expected net present value (NPV) of investing compared with the expected NPV of waiting. The expected NPV represents the discounted net value of all costs and revenues occurring throughout the time horizon as a consequence of invest-

---

[30] This price forms the basis for the rather stable forecast and determines thereby the level of price forecast throughout the time horizon

[31] Includes capture plant, all pipelines and facilitating for storage at the storage site

ing or waiting, and depends on the price paths involved and their probabilities. The expected NPV of investing consists of deterministic costs for investing and operation of the included components and - until 2018 - the expected NPV of having the option to invest in EOR.[32] The expected NPV of waiting consists of the carbon cost for the first subsequent year (which is determined by the price node in which decision is made) and the NPV of all possible timing options for the remaining years including carbon costs, capture investment and EOR investment.

The EOR investment project is evaluated annually if and only if the capture investment in undertaken.[33] The last year it may be decided on is 2020.[34] The expected value of investing consists of deterministic costs for investing and operation of the included EOR specific components and the expected NPV of the extra oil revenue which is dependent on the stochastic crude oil price. The expected value of waiting simply consists of the expected NPV of postponing the decision one more year.

In the main investment path, the capture investment decision and the EOR investment decision are both taken as late as possible for EOR to be possible. We will in the following discuss why this is very likely to be the optimal strategy.

Capture decision

A clear characteristic of the capture timing decision in the main investment path is that it is made just in time for allowing EOR to be implemented in the value chain. Deciding on building the capture plant earlier would either open for earlier EOR, which we will discuss in the next sub-section, or require storage until EOR is implemented. As it is not very likely that earlier capture will be optimal, the expected NPV of investment paths with earlier capture is worse for the majority of price paths, than the expected NPV of making the investment decision in 2018. Evidently, as it is more likely that earlier capture investment is optimal, the present value of the extra costs occurring when investing in capture earlier, does for a large majority of carbon price paths exceed the discounted carbon costs which might have been avoided. We need to analyze the costs which actually occur in order to understand this mechanism.

The positive contribution to the expected NPV for investing in capture late consists of:

- annual operating costs occurring for less years

---

[32] If EOR is to be implemented, the capture investment decision must be made no later than in 2018

[33] It is evaluated annually from the second investment year of capturing, so that investment my be carried out in in the third investment year for capture and both carbon capturing and injection for EOR may start simultaneously the following year.

[34] CO_2-injection cannot start after 2022. The latest decision for implementing EOR is therefore in 2020, giving investment in 2021 and injection start in 2022.

- cost reduction for capture technology
- discounting of investment costs over more years

The negative contribution to the expected NPV for investing in capture late consists of:

- carbon costs occurring every year until capture investment is completed
- no early extra oil revenue (loss of possibility of earlier EOR investment implies loss of possibility of a share of the total extra oil volume sold early, and thereby discounted over less years)[35]

When, as in most price paths, capture earlier than required for EOR is not profitable, the negative contribution must dominate the positive contribution. We will now evaluate the actual impacts of the above mentioned factors on the timing of the investments.

One interesting trade-off is that between annually occurring operating costs versus avoided carbon costs (if early capture is decided on, vice versa if late capture). The operating costs without EOR, i.e. the operating costs for capture, pipelines and storage, amount to 79.2 mill EUR every year, of which capture alone counts for 74.8 mill EUR. The carbon price forecast is 35 EUR/tonne throughout the time horizon, and the annually captured amount of CO_2 is 2 Mtonnes. Consequently, based on the forecast, the expected annual carbon cost corresponds to 70 mill EUR. It is however crucial to realize that this value due to the stochastic price development may differ greatly from the forecast. The operating costs are according to this reasoning *expected* to exceed the carbon costs, and for all price realizations where this is true, the incentive for capturing for the sake of avoiding the carbon costs is unreasonable.

The sensitivity analysis for the operating costs for capture implied that the capture timing is indeed sensitive to this costs, supporting the rationale above. The capture investment is inclined to be carried out earlier when this cost decreases.

It is extremely unlikely that it will be optimal to implement EOR earlier than in the main path. Hence, the contribution from discounting a share of the revenue over less years is so little dominating that we disregard this factor.

Implementing capture implies investment costs for capture as well as the investment costs for pipelines and storage facilities. The NPV of the sum of these costs is decreasing the later the investment is carried out due to two factors;

---

[35] The total volume of extra oil recovered does not increase by implementing EOR earlier, but the annual amount decreases.

the discounted cash flow and the cost reduction from capture technology development. This NPV is illustrated in Figure 50. The investment costs encourage late investment. The annual change in the years before the main capture investment year 2018 is however about 37 mill EUR, and significantly smaller than the impact of adding one of several years of operating cost. The background data for the graph is given in Appendix F. The sensitivity analysis showed that the timing is not sensitive to changes in the capture investment cost or discount rate.

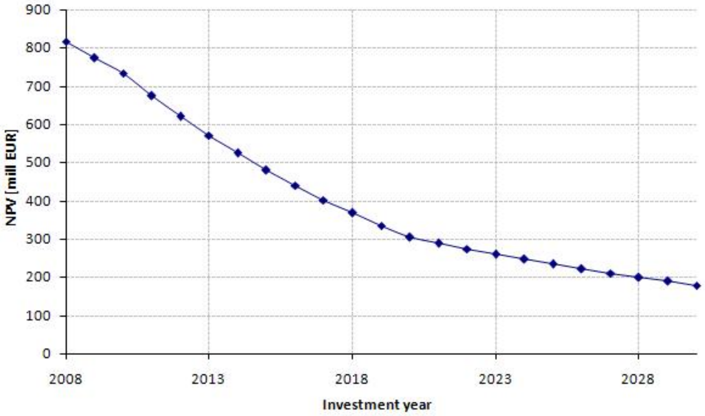


Figure 50: *NPV of investment costs for capture, pipelines and storage depending on investment year*

Before 2018 the expected value of waiting is due to the factors explained in the discussion above, higher than that of investing. It should indeed be noted that with the carbon price forecast given by Deutche Bank, the carbon prices are not high enough for encouraging capture and storage alone.

In 2018 the expected NPV of waiting does no longer include the possibility of investing in EOR in the future and thereby obtaining extra oil revenues. As the full cost picture described above favors a late investment, and the EOR option will disappear after this year, 2018 stands out as the optimal decision year for the capture investment in the majority of possible price realisations. The NPV of investing later will be favorable in a very small number of price paths.

EOR decision

In the main investment path it is optimal to implement EOR as late as possible, i.e. CO_2 injection from 2022. As the capture decision is made in 2018, EOR decision may not be considered earlier than 2020 (the second year of capture investment). It may neither be considered later. In practice, taking the previous sub-section into consideration, EOR may be decided implemented in 2020 or never. This does however not imply that the EOR timing is inflexible. Quite conversely the costs and expected revenues from EOR strongly affects the wait or invest capture decision. If it were more profitable to start EOR earlier this would have been reflected in the expected value of capture investment. The timing of EOR to start when the capture investment is done, expresses that the capture should not be built before the carbon is used for EOR.

The EOR decision is only evaluated if capture investment is already decided. The wait decision for EOR implies consequently storage of CO_2 in the Alpha structure the coming . The investment decision for EOR implies revenues, which are given by the net present expected value from all possible crude oil price paths and their probabilities, as well as the EOR investment costs and operating costs.

As explained earlier in this section, it is very likely that the total revenues from EOR exceed the total costs in most price paths, so that it is optimal to invest in EOR. That being established, why is it actually beneficial to implement EOR as late as possible? The total amount of extra oil is fixed so that the amount recovered annually equals the total amount divided over the number years where extra oil occurs. Thereby the revenue contribution on the NPV of early EOR investment is minor, only affected by a share of the oil revenue discounted over less years. The positive contribution to the expected NPV of investing in EOR late consists of cost reduction for separation technology, discounting of investment costs over more years and, very importantly, the less years of operating costs.

7.3 The real options approach

As far as we know, the timing of CO_2 value chains with EOR has not been examined for any similar norwegian case before. We would now like to give our opinion on how useful the uncertainty implementation and flexibility offered by the real options approach were to evaluate the timing decision.

With respect to the uncertainty in carbon and oil prices, the approach did not prove to change decision timing or give better expected NPV than when applying deterministic crude oil and carbon prices. This does not mean that including stochastic prices in timing decision for CO_2 value chains with EOR is never relevant. It merely indicates that the price levels and the price uncertainty employed in this thesis do not matter much for the timing in this specific case. The carbon market is new, and it is not yet an established fact that it serves the purpose of encouraging carbon emission reductions. Should it turn out that, in line with our results, the carbon price is too low to serve its purpose, it may very well be subject to sudden and significant price jumps. When the next phase of the Kyoto Protocol is entered in 2012, a price jump may be a possible feature in order to increase the impact of quotas on emissions. If the forecast were higher, the uncertainty might have played a more important role for the timing decisions.

Likewise, the crude oil price uncertainty does not affect the timing significantly. The level of the applied forecast is so high that it is very likely that EOR revenues leave a profit after all investment and operating costs for capture, storage and EOR are covered. Due to the assumptions concerning EOR, the EOR timing is almost fixed in advance. Firstly, according to the assumption that implemented EOR will last until field shut-down in 2030, the timing is only flexible with respect to start. Secondly, the total amount of extra oil is fixed, which to a certain degree fixes the extra oil revenue potential. Lastly, as outlined earlier in this section, the operating costs for EOR are high. These factors give that fluctuations in oil price need to be very elevated for the investment decisions to be affected by the uncertainty. The uncertainty matters in a few cases where oil prices are either i) very low so that no EOR investment is carried out, or ii) very high so that obtaining a share of the revenues a year or two earlier actually is profitable. If the expectaitions of the oil prices were lower, the uncertainty might have affected the investment rate to a larger degree. If the expections of the oil prices were higher, it might be more likely that it is profitable to invest in EOR earlier.

Realization of timing flexibility did, oppositely of the uncertainty implementation, prove to be constructive. Opening for invest or wait-decisions as opposed to the invest or reject-decisions offered by static models, the real options approach pointed out the investment timing decisions which are expected to be optimal in given price paths. Due to the fact that it actually seems optimal to postpone the investments and thereby the investment decisions, the dynamic model gave useful information.

7.4 Comparison with other studies

It is appropriate to compare our result with those of others. Different CO_2 value chain studies use several assumptions and contexts, and this thesis also has its own characteristics. This makes it hard to put them side by side directly. It should additionally be mentioned that the four typical problem areas of CO_2 value chains, listed in section 2.4, are not present in the context chosen for this thesis. This makes the situation look better than it might be in that of other studies.

The way we in our context look at profitability, is by comparing the NPV of the value chain with the NPV of paying quotas. Additionally, as opposed to the NPV method, we let the investment timing be flexible. To be able to compare with the results of others using the NPV method, we must look at our model in a static way and then compare the result that would appear in such a situation. In section 6.4 some evaluations are made concerning a static perspective. Firstly, if we consider capture combined with storage only, and suppose capture is invested in in the first year (2018), the NPV would be -2058 mill EUR (taken from section 6.4). This is even lower than that of paying quotas (NPV= -1 194 mill EUR), which means that capture and storage is not profitable in our analysis, from the perspective of a static NPV method. Secondly we may look at the chain present in the main investment path, which means we include also EOR. The expected NPV from a now-or-never context is also here calculated, referring to capture investment decision in the first year (2008) with EOR as early as possible (in 2013). The result is calculated to be -850 mill EUR. In this setting, the value chain of our thesis looks profitable compared to paying quotas (-1194 mill EUR), and results in an expected saving of 346 mill EUR. This result differs from most other studies, which usually claim the chain including EOR to be non-profitable. What could be the reason why our model encourages investments to a larger degree?

Other studies often apply conservative oil prices, so that the revenue potential from EOR is dramatically worse than in our thesis. This could lead to less attractive value chain investments, even though the future oil prices may result in vast revenues.

The discount rate is set rather low in this thesis, compared to other studies.[36] The sensitivity analysis proved, however, that the results are not sensitive to changes in the discount rate within the interval 5-8 %.

It has turned out that considering the value chain as a real option has a considerable profit potential. The real option value of this thesis gives an expected NPV of -191 mill EUR, resulting in a saving as high as 669 mill EUR. This speaks for the importance of including flexibility when considering the CO_2 value chain.

7.5 Impacts of the commercial incentives

Having analysed the value chain, it is interesting to look back to the commercial incentives for implementing CO_2 value chains with EOR, which were presented in section 2; i) avoidance of carbon emissions by means of carbon costs and ii) revenues from extra oil. We have established the fact that in the Tjeldbergodden-Heidrun-Alpha case study it will most likely be profitable to implement the value chain, or more accurately less unprofitable than not investing. We may also come to the conclusion that the profitability exclusively derives from the second incentive. The carbon prices are very unlikely to be high enough for capture investments to be carried out before what is necessary for meeting the optimal EOR timing. Even less likely is it that capture and storage will be implemented without EOR.

The first incentive has been created as a consequence of the Kyoto Protocol carbon emission reduction goals. Within this thesis[37] both EOR and storage

---

[36] 5.5 %

[37] EOR does not qualify for emission quota exemption as of today.

are accepted responses to this incentive. Due to investment and operating costs, it is evident that EOR will not dominate storage in the Alpha structure for the purpose of reacting to the first incentive. Storage is optimal only if carbon prices alone suggest capture so that capturing CO_2 is optimal before it is needed for injection at the production field, or after the EOR time window. As we have discussed above, EOR should only be implemented earlier in case of high oil prices. Consequently, storage timing depends on a trade-off between the carbon prices and the operating costs for EOR.

As capture and storage alone is not a recommended investment path, we may argue that the value of storage is zero. In light of the current, global focus on reducing the carbon emissions, it is important to note that the carbon price level in the forecast provided by Deutche Bank, is not high enough to encourage capture and storage (within the applied assumptions and conditions of this thesis). Keeping in mind that the emission quotas are introduced exclusively in order to reduce emissions, it is clear that the incentive does not serve its purpose if paying the carbon costs is cheaper than carrying the costs of reducing emissions.

When we by means of sensitivity analysis investigated the impacts of higher carbon prices for this value chain, we found that increasing the constant price of the forecast from 35 EUR/tonne to 62 EUR/tonne, the share of simulations where it was optimal to introduce capture and storage earlier than EOR (i.e. capture early due to carbon costs only), increased from 1 % to 35 %. Hence, in most price paths capture was still optimal because of EOR. And in the cases where capture was optimal earlier, it was, with decreasing frequency, only one, two or three years earlier than in the main investment path.

We wanted to investigate how high the carbon price would need to be in a similar value chain to that in this thesis, without the possibility for EOR, i.e. a value chain which exclusively is based upon the carbon emission mitigation incentive. The investment rate was examined for carbon prices increasing from the applied value from Deutche Bank of 35 EUR/tonne where investment was completely unlikely, to 75 EUR/tonne where investment would be the optimal strategy for all price realizations. At prices below 68 EUR/tonne not investing is more likely to be optimal than investing.

Based on assumptions in this thesis, it seems like the carbon price needs to be at a level around 75 EUR/tonne in order for capture and storage to be employed as a mitigation measure. This may on the other hand imply that, if such carbon prices do not occur, authorities may have to offer subsidies in order to encourage capturing if they want capture and storage to play a role in meeting the Kyoto goal in Norway.

The second incentive (EOR revenues) is met by creating the suggested value chain. The discounted revenues from oil sales are larger than all discounted investment and operating costs occurring if the capture and EOR investments are carried out, thus that the net contribution from EOR is positive. The value of the real option is negative due to the negative contribution of paying carbon costs until capture is fully implemented in 2022.

7.6 Other aspects

An interesting remark is that implementation of EOR with CO_2 contributes to recovering fossil fuels which might or might not have been recovered without CO_2. Hence, with respect to the first incentive, it is necessary to carry out calculations of the net contribution of CO_2 to the atmosphere by employing CO_2 for EOR. In the value chain of this thesis the oil producers make a large profit from extra oil revenues based on CO_2. Is it fair that they actually benefit from this profit? Maybe it would make more sense if society, which will have to cope with the consequences of the extra carbon emissions (in addition to benefiting from more available energy sources), would take advantage of some of the profit. We leave these issues for the reader to reflect upon.

That being said, the large, expected short-term growth in energy demand calls for as much fossil fuels as possible to be recovered. In this perspective EOR with CO_2 is indeed a favorable measure. With regards to mitigating the climate changes caused by carbon emissions, there may be carbon free solutions covering the demand in the long-run. In the short-run it does however seem inevitable to employ all available fossil fuel in order to satisfy the market.

Finally, it should not be left unmentioned that a range of political issues must be overcome before CO_2 value chains with permanent storage may be implemented. Firstly, in order to encourage private actors to involve in such projects, it may be necessary that the authorities carry the long-term leakage risk. Secondly, this long-term risk causes the public acceptance of storage to be low. The storage enthusiasts argue that, in case of future leakage, it is better that the climate changes caused by CO_2 leakage occur later than now. Climate changes now will cause at least as harmful consequences for the future generations as if they occurred later. Besides they claim that geological storage poses very small leakage risk. The opponents, on the other hand, fear that the CO_2 may have local effects where it is stored for plant life and animal life. A common understanding is needed on of how to handle CO_2 in the best way.

8 Criticism

When evaluating the results found in this study, it is important to be aware of the limitations of the model. We will now attempt to map the main weaknesses of the model and results presented in this thesis. We have chosen to differentiate between limitations in the specific mathematical model that is applied, and the weaknesses in the results caused by weak or rough assumptions that affect the results to a considerable degree.

From analysing the results an obvious observation is that the solution, in spite of the implementation of uncertainty, is extremely static. An interesting question arises from this observation; what causes this absence of dynamics in the solution? Does this have to do with the way the system is modelled? Or could the timing be indirectly imposed by the assumptions? We will discuss these issues in the following sub-sections.

8.1 Criticism of model

The proposed model is not meant to be run frequently, as its main purpose is to solve strategic investment decisions, and is therefore not dependent on extremely short calculation time. Taken this into account and that the calculation time has showed out to be acceptable, few attempts have been done to reduce the problem size from what it is today.

Some of the central features of the model makes it to a certain extent case specific, and thereby less applicable for case studies that differs slightly from the one presented here. This has particularly to do with the way we have implemented the assumption that the amount of extra oil extracted because of EOR depends on the year EOR is started. For the reason to avoid one more state variable in the model, this was solved by implementing adjustments that have made the model considerably more case specific. One more state variable would have increased the complexity of the model and increased the calculation time significantly. This still makes the model less attractive.

When it comes to user friendliness, stochastic dynamic programs are generally seen as complex models that both are complicated to understand and to use. Now when the results from the model are analysed, and the implementation of uncertainty turned out to hardly influence the results, we could in this specific case have improved the user friendliness of the model by making a deterministic model. A deterministic model would have given mainly the same results. When this is said, a deterministic model would not teach us anything about the little influence of uncertainty that is present in this value chain. A better way would perhaps be to study the importance of uncertainty in pre-studies, for then to disregard the uncertainty in the main model.

8.2 Criticism of assumptions

Some of the assumptions and simplifications that the value chain is based upon can, of different reasons, be object for criticism. The fact that some assumptions differ considerably from the real case, implies that the results may not actually be true in reality.

The following assumptions could have been changed to make the model more realistic, but are implemented for the purpose of simplification.

- It is assumed that the gas power plant at Tjeldbergodden will be operating from the start of 2008. Today we know that this is already out of reach.
- In reality a project that is started will be terminated as soon as it is no longer expected to be profitable. In the proposed model no investment paths can be terminated.
- The capture plant investment cost is assumed to be independent of the number of years it will be in operation, and no salvage value is included. In reality, the capture plant will probably have a life time that is longer than the one it will have in our system, and it will therefore have a salvage value at the end of the time horizon. This salvage value will additionally depend on the amount of years it has been operating, and thereby the year in which the investment takes place.
- Unforeseen down-times in any of the operating plants are not included in the model. If the gas power plant producing the CO_2 is down, Heidrun still needs constantly injected CO_2 . The storage reservoir Alpha is assumed to be operating in all situations where the capture plant is operating, and CO_2 recovery from Alpha could have been providing Heidrun with CO_2 in such situations. The investment in a recovery well is anyhow not included in the model, and this is thus a weakness.
- In reality, CO_2 applied for EOR does not presently qualify for carbon quota exemption. It does not seem unreasonable to assume, as we have done, that in the future EOR will be subject to exemption as long as the re-produced CO_2 is handled.

As mentioned, the proposed model gives little spread in the solutions. Some assumptions give less room for solution dynamics than other. The most obvious ones are mentioned here.

- There is no flexibility in the oil reservoir shut down time in the proposed model. In reality EOR may affect the shut down time. The timing of EOR is only flexible when it comes to the start year, not to the end year. Changes in shut down times may influence both costs and revenues considerably.

- The amount of extra oil that is available when using CO_2 for EOR is assumed to be independent of the timing of EOR and of the length of the period EOR is operating.
- There is no flexibility in the model when it comes to the choice of investing in a separation plant on Heidrun or not. There will always be a trade-off between including a separation plant (and be able to sell the natural gas) or not (and re-inject the CO_2 rich natural gas and thereby accept the loss of gas revenues). This flexibility could have been present in the model

For comparison with results from similar studies, one may notice that our results are slightly more optimistic than others. The explanation may lie in the choice of assumptions. For the purpose of this thesis, we mean that the selected assumptions are appropriate, and that they are not weaknesses in the model. Why we mention them here, is because they may be seen as weaknesses of the comparability of the model.

- The crude oil forecast we have used as a basis for the stochastic oil prices are considerably more optimistic than oil prices used in similar studies, where rather conservative forecasts are normal.
- In our calculations we have used a lower discount rate than what we have seen in similar studies. It can be argued that the risk adjustment in the discount rate could have been set higher, due to the high risk that is involved in such a value chain.
- The assumed technology development for capture plants are based on optimistic predictions.

It is additionally worth mentioning some characteristics of the assumptions that limit the validity of the results.

- Data used as basis for input parameters are taken from a range of different sources, each using different assumptions.
- All assumptions and input data that are related to the development of the carbon price are uncertain. Even if the carbon price is modelled as a stochastic element, the predictions for the oil-/carbon price correlation factor and the carbon price standard deviation are both based on historical data, which most likely is not very representative for the future.
- The operating costs for capture and separation, which constitute a significant cost in the value chain, is particularly dependent on the gas price. Because the gas price is correlated to the oil price and the oil price is modelled as a stochastic element, we could have implemented the correlation between the oil price and these operating costs.
- After year 2008 the cost data in the model is only adjusted for inflation, and not specifically adjusted according to cost increases in the specific industries.

8.3 Criticism of analysis

The covariance of parameters is omitted in the sensitivity analysis. In order to give a deeper evaluation of the robustness, sensitivity analysis for parameters which are assumed to change together, should have been included. The operating costs for capture and separation could have been varied simultaneously as oil price changes because these operating costs are greatly dependent on the gas price, which again is correlated to the oil price. Furthermore covariance of discount rate and inflation rate could have been investigated.

9 Suggestions for further work

When collecting input data concerning costs during this work we have noticed that costs related to the projects differ considerably in the available studies. Realistic representations of input data are important in order to give good solutions. We have absolutely seen the need for studies going deeper into costs in this area. Agreements about the costs must be present before anyone can discuss CO_2 value chain profitability.

We have shown that, compared to the possibility of paying CO_2 quotas, it is profitable to use CO_2 for EOR, given the assumptions that are made. Because of the high degree of uncertainty that is present (connected to new technology, reservoir reactions and unforeseen events), in addition to the extensive investment costs, the project investments imply extremely high risk for the investors. Further studies into the present risk factors are therefore crucial for investment decisions to actually be carried out. A recommendation is to go deeper into sensitivity analysis related to these elements and consider the implementation of these as stochastic parameters.

The technology development predictions are relatively optimistic in this study. The degree of reality in these predictions should be studied further.

Two specific model improvements should be implemented before the proposed model should be adopted. The extra amount of oil that is recovered when investing in EOR should be adjusted according to the injection timing. It is a fact that this amount depends on the exact injection time. This fact may have an impact on the timing decision and should therefore be implemented in the model. The decision to include a separation unit or not at Heidrun should secondly be implemented. This would imply the study of the gas price development which will in any case influence the value chain profitability considerably.

The profitability of the value chain has in this study been analysed separately from the actual operation of the gas power plant. That the net present value is negative does therefore not imply that the project is rejected, taken into account that the “doing nothing” case implies even more negative net present value. It would be of interest to study the profitability of the whole system, including the costs and revenues connected to the gas power plant.

10 Conclusion

The investment timing of the sub-projects of a possible CO_2 value chain has been investigated. We have seen that there are two main incentives for the establishment of such a chain. The first is the saving of CO_2 quotas by not emitting CO_2. The other is that of obtaining revenues by including EOR for recovery of extra oil. Work has been carried out in order to find out if the incentives were strong enough for establishing a profitable value chain.

To solve the investment decision problem, a real options approach (ROA) has been utilized, which opened for the inclusion of flexibility and uncertainty. Uncertainty has been implemented by modelling the correlated prices of crude oil and carbon. Flexibility has been included by treating the investment decisions as invest-or-postpone decisions instead of static now-or-never decisions. A stochastic dynamic program has been used as a tool for implementing the ROA.

It was shown for the investigated value chain that, with regards to the future, uncertain realization of crude oil and carbon prices, it is very likely that combining EOR with capture and storage will result more profitable (less unprofitable) than not implementing the value chain. The time window for a possible EOR initiation is assumed to be between 2013 and 2020. The results indicated that the optimal timing of the EOR decision will most likely be in 2020, hence as late as possible. We have also demonstrated that it is very unlikely that it will be optimal to invest in capture and storage without EOR. This makes it clear that the second incentive, that of obtaining oil revenues from EOR, is the one triggering the investments.

Obviously, to be able to carry out EOR, capture investment is firstly necessary. Did the incentive of avoiding CO_2 quotas influence the capture decision? The results clearly showed that it will be optimal to take this decision in 2018 so that the capture investment is completed just in time for EOR. Only if the CO_2 prices reach extremely high values, will it be better to start capturing earlier and direct the captured CO_2 to permanent storage. Carrying CO_2 quota costs will in most price realizations be preferred to paying the investment and operating costs of capture and storage. Consequently, avoiding quotas does for these reasons not represent a real incentive for investments.

Analysis has shown to which input parameters the results are most sensitive and how the timing is affected. Firstly, the late timing of capture and EOR may be explained by inclining to paying operating costs for as few years as possible. In addition, decreasing investment costs on capture over time due to technology development also contributes in delaying the decisions. Besides, it should be noted that the total amount of extra oil is independent of the timing.

For the given value chain and the price ranges applied, the uncertainty implementation of carbon and crude oil prices turned out invaluable. This is found since in the vast majority of the price paths, the decisions resulted the same. If the general level of the carbon or the price forecasts were different, the timing could however be sensitive to the uncertainty, and thereby defend the stochastic method. When it comes to adding flexibility of investment timing in the profitability calculations, this was evaluated to be very valuable in the setting of this thesis. For instance, it was shown that waiting is more profitable than starting the capture project right away, since carrying carbon costs is cheaper than running the capture plant, pipelines and storage site.

Ultimately, the CO_2 value chain implies such high investment and operation costs that considerable revenues are needed to make it profitable. For value chains where EOR is not an option, capture and storage is the only project to be considered and will only be carried out if costs are considerably reduced and/or the quota savings are of satisfying size. As of today it is cheaper to carry the carbon costs than the value chain costs, which again means that the carbon quotas do not serve the goal as implemening cabon capture and storage as a part of the climate change mitigation measures. Further research on possible cost savings on capture technology could alter the situation, so that capture and storage would be an attractive investment project.

References

Bellona (2005) *CO_2 for EOR on the Norwegian shelf – A case study*, available at www.bellona.org.

Bernard, J.-T., Khalaf, L. et.al. (2008) *Oil Prices: Heavy Tails, Mean Reversion and the Convenience Yield,* GREEN, Universitè Laval, Quèbec.

Botterud, A. and Korpås, M. (2007) *A stochastic dynamic model for optimal timing of investments in new generation capacity in restructured power systems*, International Journal of Electrical Energy and Power Systems 29, 163-174.

The CO_2 Capture Project (CCP) (2004) *Project Results - phase 1*, available at: www.co2captureproject.com.

Dagpunar, J. S. (2007) *Simulation and Monte Carlo With applications in finance and MCMC*, John Wiley & Sons Ltd, Chichester.

Deutsche Bank (2007) *Aviation Deviation: EU Parliament Sends Bullish Signal for Phase 3*, Frankfurt.

Dixit, A. K. and Pindyck, R. S. (1994) *Investment under Uncertainty*, Princeton University Press, New Jersey.

Energy Information Administration (EIA) (2008) *Annual Energy Outlook 2008*, early release (full publication will be released in May 2008),
available at www.eia.doe.gov.

Gassco, Gassnova and Petoro (2006) *Innledende forhandlinger mellom de kommersielle aktørene i en CO_2-kjede*, available at www.regjeringen.no.

Hull, J. C. (2006) *Options, Futures and Other Derivatives*, 6th ed., Pearson Prentice Hall, New Jersey.

The International Energy Agency (IEA) (2008) *Natural Gas Market Review 2007- Security in a Globalising Market to 2015*, Paris.

The Intergovernmental Panel on Climate Change (IPCC) (2005) *Carbon dioxide Capture and Storage*, Cambridge University Press, Cambridge.

The Intergovernmental Panel on Climate Change (IPCC)(2007) *Fourth Assessment Report: Climate Change 2007*, available at www.ipcc.ch

Kall, P. and Wallace, S. W. (1994) *Stochastic Programming*, 1st ed., John Wiley and Sons, Chichester.

Kreps, D.M. (2004) *Microeconomics for managers*, W. W. Norton & Company, New York.

McDonald, R. L. (2006) *Derivatives Markets*, 2nd ed., Pearson International Edition, Pearson Education, Inc., Boston.

The Norwegian Ministry of Finance (NMF) (2005) *Rundskriv R-109/2005*, available at www.regjeringen.no.

The Norwegian Ministry of Finance (NMF) (2005) *Veileder i samfunnsøkonomiske analyser*, available at www.regjeringen.no.

The Norwegian Petroleum Directorate (NPD) (2005) *CO_2 for økt oljeutvinning på norsk sokkel – en mulighetsstudie,* available at www.npd.no.

The Norwegian Petroleum Directorate (NPD) (2007) *Fakta Norsk Petroleumsverksemd 2007*, available at www.npd.no.

The Norwegian Water Resources and Energy Administration (NVE) (2005) *Gasskraft med CO_2-håndtering - Verdikjedevurderinger*, available at www.nve.no.

Pindyck, R. S. (1999) *The Long-Run Evolution of Energy Prices*, The Energy Journal 20, 1—27.

Pindyck, R. (2001) *The dynamics of commodity spot and futures markets: A primer.* The Energy Journal 22, 1–29.

Rubinstein, M. (1995) *Rainbow options,* published under the title *Return to Oz*, RISK 7, 67-71.

Conversations with Petter Røkke, SINTEF Energy Research, Trondheim, spring 2008.

Schwartz, E.S. and Smith, J.E. (2000) *Short-Term Variations and Long-Term Dynamics in Commodity Prices*, Management Science 46(7), 893–911.

The Norwegian Pollution Control Authority (SFT)(2005) *Reduksjon av klimagassutslipp i Norge. En tiltaksanalyse for 2010 og 2020,* available at www.sft.no.

SINTEF Energy Research (2005) *Tjeldbergodden power/methanol – CO_2 reduction efforts*, available at www.energy.sintef.no.

Statkraft (2007) *Handel med klimakvoter*, available at www.statkraft.no.

StatoilHydro and Fluor (2005) *Tillegg til konsekvensutredning for utvidelse av metanolfabrikk og bygging av gasskraftverk på Tjeldbergodden,* available at www.statoil.com.

Conversations with Dr.Ing. Tore Torp, StatoilHydro, Trondheim, spring 2008.

Wallace, S. W. (2000) *Decision Making under Uncertainty: Is Sensitivity Analysis of Any Use?* Operations Research 48(1), 20-25.

Wallace, S. W. (2002) *Decision making under uncertainty: The art of modeling,* Molde University College, Molde.

Yang, M. and Blyth, W. (2007) *Modeling Investment Risk and Uncertainties with Real Options Approach*, International Energy Agency (IEA) Working Paper Series LTO/2007/WP 01, Paris.

Yao, W.-M. et al. (2006) *G 33 Monte Carlo Techniques*, available on http://pdg.lbl.gov.

Zerbe, R.O. (1994) *Benefit-cost analysis in theory and practice*, HarperCollins College Publishers, New York.

A Appendix

Gas power plant at Tjeldbergodden

Status of gas power plant

In April 2003 Statoil reported that they wanted to expand the methanol production at Tjeldbergodden. They saw it as a strategic choice to combine the expansion with the construction of a gas power plant. This fact was underlined when Statoil sent their gas power plant permit application for Tjeldbergodden to NVE in august 2004. In January 2006 the permit was granted. CO_2 from power production is subordinated quota exemption according to national quota laws and regulations ("Klimakvoteloven" and "Klimakvoteforskritften") which are active since 01.01.2005. The Norwegian Pollution Control Authority (SFT) advised the Ministry of the Environment (MD) to require full CO_2 handling systems installed at Tjeldbergodden before power production started. Hence, no power production will take place until capturing and handling systems are included.

The need for a gas power plant

Even though Norway in general has an electricity surplus, the region around Tjeldbergodden occasionally suffers a deficit. The region sees an increasing demand for energy supply in the near future. Hence, a gas power plant will enforce the regions capability of being self-supplied with energy. In addition, a gas power plant will contribute to enforcing the Norwegian and Nordic energy balance in dry years where the Norwegian main source of energy, water, is scarce. The gas power plant has an efficiency of 860 MW and will contribute with a yearly supply of 7 TWh, which approximately corresponds to 6% of the 120 TWh Norwegian yearly electricity production[38].

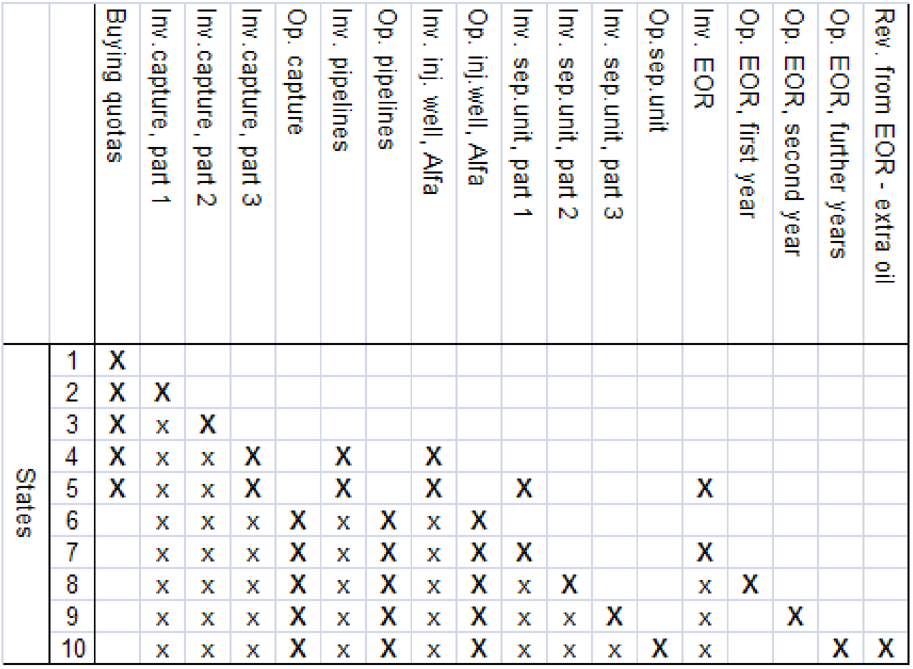
---

[38] www.statoilhydro.com

B Appendix

Revenues and costs connected to states

Figure 51 gives an overview of the revenues and costs connected to each state. Capital X in the figure means that these are costs and revenues that occur in the state in question. Small x means that these investments are already done when standing in this state. Note that revenues from EOR only occur after two years of EOR operation, which is state 10.



		Buying quotas	Inv.capture, part 1	Inv.capture, part 2	Inv.capture, part 3	Op. capture	Inv. pipelines	Op. pipelines	Inv. inj. well, Alfa	Op. inj.well, Alfa	Inv. sep.unit, part 1	Inv. sep.unit, part 2	Inv. sep.unit, part 3	Op.sep.unit	Inv. EOR	Op. EOR, first year	Op. EOR, second year	Op. EOR, further years	Rev. from EOR - extra oil
States	1	X																	
	2	X	X																
	3	X	x	X															
	4	X	x	x	X		X		X										
	5	X	x	x	X		X		X		X				X				
	6		x	x	x	X	x	X	x	X									
	7		x	x	x	X	x	X	x	X	X				X				
	8		x	x	x	X	x	X	x	X	x	X			x	X			
	9		x	x	x	X	x	X	x	X	x	x	X		x		X		
	10		x	x	x	X	x	X	x	X	x	x	x	X	x			X	X

Figure 51: *Costs and revenues of states*

C Appendix

Special feature of the stochastic dynamic program

The main part of the stochastic dynamic model is slightly different from the pseudo code given in section 5.2.4. This is because the annual amount of extra oil, that is recovered when investing in EOR, depends on the year in which EOR was started. Only state 10 (operation of EOR, third year and onwards) is affected by the revenue from extra oil. As soon as one knows in which period the state transition from state 9 (second year of operation of EOR) to state 10 is done, one implicitly knows what will be the annual amount of extra oil that will be available for the rest of the time horizon. To solve this mathematically, the loop explained in section 5.2.4 is in reality solved as two separate loops; one for state 9 and 10 and one for states 1-8. The last loop is similar to the one described in section 5.2.4. The pseudo code for the first loop is given in the box below.

```
Initialisations
$p := (P-1)$

Repeat: until $p = 1 \mid SLOG_{9\,10\,p} = 1$

    Initialise: $n = 1$

    Repeat: until $n = N \mid NLOG_{n\,P} = 1$

        Calculate: $\Pi OPT_{10\,n\,P}$(extra oil amount $= OIL_p$)

    Initialise: $t := P-1$

    Repeat: until $t = P - p$

        Initialise: $n = 1$

        Repeat: until $n = N \mid NLOG_{n\,t} = 1$

            Calculate: $E\Pi OPT_{10\,n\,t+1}$and $\Pi OPT_{10\,n\,t}$
                (extra oil amount $= OIL_p$)
    Initialise: $n = 1$

    Repeat: until $n = N \mid NLOG_{n\,p} = 1$

        Calculate: $\Pi_{9\,n\,p}$

        Set: $\Pi OPT_{9\,n\,p} := \Pi_{9\,n\,p}$ and $BEST_{9\,n\,p} = 10$

Output: $BEST_{9np}$and $\Pi OPT_{9np}$
```

Where ΠOPT_{inp} and $E\Pi OPT_{inp}$ are as described in section 5.2.4 except from that OIL_{ip} is now replace by OIL_pwhich is the annual amount of extra oil when going from state 9 to state 10 in time period p (Notice that p refers to the time period where we are in state 9).

D Appendix

Input data

Some of the cost input data is given in Table 12.

Cost	Value	Taken from
CAPEX, capture	472 mill EUR	(StatoilHydro and Fluor 2005)
OPEX, capture	75 mill EUR	(StatoilHydro and Fluor 2005)
CAPEX, pipelines	288 mill EUR	(SINTEF 2005)
OPEX, pipelines	1% of CAPEX	(Torp 2008)
CAPEX, storage	56 mill EUR	(NVE 2005)
OPEX, storage	0.249 mill EUR pr. year	(Torp 2008)
CAPEX, EOR	13.9 mill EUR	(Torp 2008)
OPEX, EOR	5% of CAPEX	(Torp 2008)
CAPEX, sep.unit	472 mill EUR	(StatoilHydro and Fluor 2005)
OPEX, sep.unit	75 mill EUR	(StatoilHydro and Fluor 2005)

Table 12: *Cost data*

E Appendix

Data sensitivity analysis

Most of the data found in the sensitivity analysis are given in tables below. BC is an abbreviation for Base Case.

Carbon prices

Volatility

Volatility	Value of real option [mill EUR]	Capture and EOR	Only capture	No investments	Investment rate	Rate of changed investment paths
0	-192	99.91 %	-	0.09 %	99.91 %	0.00 %
0.05	-191	98.98 %	-	1.02 %	98.98 %	0.17 %
0.0775	-191	98.87 %	-	1.13 %	98.87 %	1.28 %
0.1	-190	98.97 %	-	1.03 %	98.97 %	3.84 %
0.15	-185	98.23 %	-	1.77 %	98.23 %	9.16 %
0.2	-176	96.24 %	-	3.76 %	96.24 %	15.25 %
0.3	-149	94.53 %	-	5.47 %	94.53 %	21.65 %
0.5	-82.8	94.64 %	-	5.36 %	94.64 %	22.20 %
1	1	94.44 %	-	5.56 %	94.44 %	10.56 %

Table 13: *Sensitivity data - carbon price volatility*

Price forecast

Constant carbon price forecast [EUR/tonne]	Constant carbon price forecase [NOK/tonne]	Value of real option [mill EUR]	Capture and EOR	Only capture	No investments	Investment rate	Rate of changed investment paths
~ 0	1	632	94.57 %	-	5.43 %	94.57 %	-
13	100	339	94.37 %	-	5.63 %	94.37 %	-
25	200	45.0	98.91 %	-	1.09 %	98.91 %	0.04 %
35 (BC)	280	-191	98.91 %	-	1.09 %	98.91 %	1.23 %
37	300	-247	96.65 %	-	3.35 %	96.65 %	2.36 %
50	400	-532	99.53 %	-	0.47 %	99.53 %	22.58 %
62	500	-778	99.91 %	-	0.09 %	99.91 %	35.01 %

Table 14: *Sensitivity data - carbon price forecast*

Crude oil price

Volatility

Volatility	Value of real option [mill EUR]	Capture and EOR	Only capture	No investments	Investment rate	Rate of changed investment paths
0	-192	100%	-	-	100.00 %	0.70 %
0.05	-192	100%	-	-	100.00 %	0.76 %
0.0775	-191	98.95%	-	1.05 %	98.95 %	1.21 %
0.1	-186	94.88%	-	5.12 %	94.88 %	2.23 %
0.12	-179	94.50%	-	5.49 %	94.51 %	2.74 %
0.15	-160	82.96%	-	17.04 %	82.96 %	6.87 %
0.2	-121	82.42%	-	17.58 %	82.42 %	11.05 %
0.3	-10.9	62.32%	-	37.68 %	62.32 %	18.77 %
0.4	67.1	41%	1,13 %	57.87 %	42.13 %	37.87 %
0.5	124	33.21%	5,39 %	61.40 %	38.60 %	43.13 %
0.6	86.4	33.27%	5,69 %	61.04 %	38.96 %	43.64 %
1	-623	6.77%	4,67 %	88.56 %	11.44 %	49.06 %

Table 15: *Sensitivity data - crude oil price volatility*

Price forecast

Price forecast [EUR/barrel]	Price forecast [USD/barrel]	Value of real option [mill. EUR]	Capture and EOR	Only capture	No investments	Investment rate	Rate of changed investment paths
10	15.8	-1190	0.22 %	-	99.78 %	0.22 %	20.72 %
20	31.5	-1170	12.60 %	-	87.40 %	12.60 %	5.60 %
30	47.3	-1040	53.08 %	-	46.92 %	53.08 %	1.38 %
40	63.1	-790	82.58 %	-	17.42 %	82.58 %	0.85 %
50	78.9	-484	94.62 %	-	5.38 %	94.62 %	0.80 %
60	94.6	-161	98.97 %	-	1.03 %	98.97 %	0.79 %
70	110	166	99.89 %	-	0.11 %	99.89 %	1.22 %
80	126	493	100.00 %	-	-	100.00 %	2.13 %
100	158	1150	100.00 %	-	-	100.00 %	5.55 %

Table 16: *Sensitivity data - crude oil price forecast*

Correlation

Correlation factor	Value of real option [mill EUR]	Capture and EOR	Only capture	No investments	Investment rate	Rate of changed investment paths
0	192	99.78 %	-	0.22 %	99.78 %	0.47 %
0.2	192	99.52 %	-	0.48 %	99.52 %	0.86 %
0.4	191	99.31 %	-	0.69 %	99.31 %	0.87 %
0.6	191	99.14 %	-	0.86 %	99.14 %	1.00 %
0.8	191	98.98 %	-	1.02 %	98.98 %	0.79 %
0.87 (BC)	191	98.87 %	-	1.13 %	98.87 %	1.28 %
1	191	98.93 %	-	1.07 %	98.93 %	1.95 %

Table 17: *Sensitivity data - correlation factor*

Discount rate

Discount rate	Value of real option [mill EUR]	Capture and EOR	Only capture	No investments	Investment rate	Rate of changed investment paths
5%	-136	98.89 %	-	1.11 %	98.89 %	0.86 %
5.5% (BC)	-191	98.87 %	-	1.13 %	98.87 %	1.28 %
6%	-238	98.88 %	-	1.12 %	98.88 %	1.30 %
6.5%	-279	98.87 %	-	1.13 %	98.87 %	2.25 %
7%	-314	98.92 %	-	1.08 %	98.92 %	2.28 %
7.5%	-344	98.69 %	-	1.31 %	98.69 %	2.61 %
8%	-370	98.13 %	-	1.87 %	98.13 %	3.79 %

Table 18: *Sensitivity data - discount rate*

Selected cost parameters

Investment costs for capture- and separation plant

Investment cost capture/ separation	Value of real option [mill EUR]	Capture and EOR	Only capture	No investments	Investment rate	Rate of changed investment paths
Constant (2008 BC)	-485	93.97 %	-	6.03 %	93.97 %	5.14%
60% of BC	-55.6	99.89 %	-	0.11 %	99.89 %	4,27 %
70% of BC	-89.6	99.51 %	-	0.49 %	99.51 %	2,38 %
80% of BC	-123	99.09 %	-	0.91 %	99.09 %	2,30 %
90% of BC	-157	98.97 %	-	1.03 %	98.97 %	1,85 %
BC	-191	98.91 %	-	1.09 %	98.91 %	1.16%
110% of BC	-224	98.96 %	-	1.04 %	98.96 %	0,80 %
120% of BC	-258	98.63 %	-	1.37 %	98.63 %	0,62 %

Table 19: *Sensitivity data - CAPEX capture/ storage*

Operating costs for storage

OPEX storage [mill. EUR]	Value of real option [EUR]	Capture and EOR	Only capture	No investments	Investment rate	Rate of changed investment paths
0% of BC	-189	98.95 %	-	1.05 %	98.95 %	1.20 %
50% of BC	-190	98.92 %	-	1.08 %	98.92 %	1.32 %
BC	-191	98.87 %	-	1.13 %	98.87 %	1.28 %
150% of BC	-191	98.96 %	-	1.04 %	98.96 %	1.20 %
200% of BC	-192	98.94 %	-	1.06 %	98.94 %	1.16 %

Table 20: *Sensitivity data - OPEX storage*

Operating costs for capture and separation

OPEX capture/ separation [mill. EUR]	Value of real option [mill EUR]	Capture and EOR	Only capture	No investments	Investment rate	Rate of changed investment paths
0	814	100.00 %	-	-	100.00 %	100.00 %
15	490	100.00 %	-	-	100.00 %	100.00 %
30	256	100.00 %	-	-	100.00 %	63.25 %
45	94.2	99.98 %	-	0.02 %	99.98 %	23.81 %
60	-51.5	99.87 %	-	0.13 %	99.87 %	5.88 %
75	-193	98.88 %	-	1.12 %	98.88 %	1.32 %
90	-331	95.54 %	-	4.46 %	95.54 %	0.13 %
105	-465	94.27 %	-	5.73 %	94.27 %	0.03 %
120	-589	83.05 %	-	16.95 %	83.05 %	-
135	-706	81.73 %	-	18.27 %	81.73 %	-
150	-805	62.43 %	-	37.57 %	62.43 %	-

Table 21: *Sensitivity data - OPEX capture/separation*

F Appendix

NPV of capture and storage invstment costs

The table below shows the basis for the calculation of net present value of capture, storage and pipeline investment costs.

Investment year	CAPEX inv. adjustet for cost reduction of technology [mill EUR]	Total capture and storage investments costs [mill EUR]	NPV of total capture and storage investment costs [mill EUR]
2008	472	816	816
2009	472	816	774
2010	472	816	733
2011	449	793	675
2012	425	769	621
2013	401	745	570
2014	377	722	523
2015	354	698	480
2016	331	675	440
2017	307	651	402
2018	283	627	367
2019	260	604	335
2020	236	580	305
2021	236	580	289
2022	236	580	274
2023	236	580	260
2024	236	580	246
2025	236	580	233
2026	236	580	221
2027	236	580	210
2028	236	580	199
2029	236	580	188
2030	236	580	179

Table 22: *NPV of capture and storage investment costs dependent of investment year*

G Appendix

Complete XpressMP code

```
!Master thesis, NTNU, May 2008
!Marte Aaberg, Kristin Ljønes and Kristin Lien
!SDP for CO2 value chain


model ModelName
uses "mmxprs";                          !gain access to the Xpress-Optimizer solver

declarations

P: integer                              !No of time periods [-]
S: integer                              !No of simulations [-]
NO_OF_STATES: integer                   !No of states  [-]
NO_OF_NODES: integer                    !No of nodes giving CO2- and oil prices [-]
rows_opex: set of integer
rows_rev: set of integer
rows_capex: set of integer

end-declarations

!#############################################################################################
initializations from "mmodbc.odbc:data_for_model.xls"
P as "END"
S as "NO_SIMULATIONS"
NO_OF_STATES as "NO_STATES"
rows_opex as "rows_opex"
rows_rev as "rows_rev"
rows_capex as "rows_capex"

end-initializations
!#############################################################################################
```

```
declarations
periods= 1..P
end-declarations


!Calculating the number of nodes.
NO_OF_NODES:= sum(p in periods)p*p


declarations

!Sets

!A state is the result of all decisions made so far (investment and operation)
!A node consists of one oil-price and one CO2-price
states=1..NO_OF_STATES
nodes=1..NO_OF_NODES
simulations=1..S

!Parameters to be imported from Excel:
        ! Costs and revenues
OPEX_FACTOR: array (rows_opex,states)of real         !=1 if state s  implies OPEX no. ro [-]
REV_FACTOR: array (rows_rev,states) of real          !=1 if state s implies revenue no. rr [-]
CAPEX_FACTOR: array (rows_capex,states) of real      !=1 if state s implies CAPEX no. c [-]

TOT_OIL_PRODUCE: real                                !Total amount of produceable oil at the oil field [barrels]
EOR_RATE: real                                       !Percentage of producable oil that may be recovered due to CO2 injection [-]

I_EOR: real                                          !Investment cost for EOR [MNOK]
OPEX_EOR: real                                       !Op.cost for EOR [MNOK]

I_CAPT_20: array(periods) of real                    !Inv.cost capture, first investment year, when we are in time t [MNOK]
I_CAPT_40a: array(periods) of real                   !Inv.cost capture, second investment year, when we are in time t [MNOK]
I_CAPT_40b: array(periods) of real                   !Inv.cost capture, third investment year, when we are in time t [MNOK]
```

```
OPEX_CAPT: real                                 !Op.cost of capture installation [MNOK]

I_STORAGE: real                                 !Investment cost of Alpha (well) [MNOK]
OPEX_STORAGE: real                              !Supervision costs of storage, fixed pr.year [MNOK]

I_ALLPIPES: real                                !Inv.cost of all pipes [MNOK]
OPEX_PIPES: real                                !Op.cost for all pipes [MNOK]

I_SEP_20: array(periods) of real                !Inv.cost separation, first investment year, when we are in time t [MNOK]
I_SEP_40a: array(periods) of real               !Inv.cost separation, second investment year, when we are in time t [MNOK]
I_SEP_40b: array(periods) of real               !Inv.cost separation, third investment year, when we are in time t [MNOK]
OPEX_SEP: real                                  !Op.cost separation unit [MNOK]

I: array(rows_capex,states,periods) of real     !CAPEX no. rc in state s, time period p (NOTE! The different inv.costs are not included in every state!) (in 2008-NOKs) [MNOK/year]
O: array(rows_opex,states,nodes) of real        !OPEX no. ro in state s, CO2 state sc, oil state so (in 2008-NOKs ) [MNOK/year]

        !Parameters for stochastics:
STD_CO2: real                                   !Standard deviation, CO2 prices [-]
STD_OIL: real                                   !Standard deviation, oil prices [-]
DT: real                                        !Time resolution [years]
CORR: real                                      !Correlation factor CO2/oil [-]
r: real                                         !discount rate [-]
INFL: real                                      !inflation rate [-]
PROG_OIL: array (1..P+1)of real                 !Oil price prognosis in time t [MNOK/barrel]
PROG_CO2: array (1..P+1)of real                 !CO2 price prognosis in time t [MNOK/tonnes]
PROB: real                                      !Probability to go to another node = 0,25 [-]
UP: real                                        !Up factor crude oil, nonrectangular tree [-]
DOWN:real                                       !Down factor crude oil, nonrectangular tree [-]
A:real                                          !Carbon price factor for oil up, nonrectangular tree [-]
B:real                                          !Carbon price factor for oil up, nonrectangular tree [-]
C:real                                          !Carbon price factor for oil down, nonrectangular tree [-]
D:real                                          !Carbon price factor for oil down, nonrectangular tree [-]
```

```
        !General parameters:
FLOW: real                                                   !CO2-flow from TBO in [MTonnes/year]
A_2D: array(states,states) of integer                        !State transition logic [-]

!Parameters to be calculated in the model:

A_3D: array(states,states,1..P-1) of integer                 !=1 if transition from one state to another, in time t is possible, else it is 0 [-]
SLOPE_CO2: real                                              !Slope of the CO2 prognosis [-]
SLOPE_OIL: real                                              !Slope of the oil prognosis [-]
PRICE_OIL: array(nodes)of real                               !Price of oil in a certain price node [MNOK/barrel]
PRICE_CO2:array(nodes)of real                                !Price of co2 in a certain price node [MNOK/MTonne]
EXTRA_OIL: array(periods) of real                            !Annual amount of oil recovered when being in state 9 in period p [barrels/year]
EXTRA: array(simulations) of real


PROF: dynamic array(states, nodes, periods)of real           !Profit in state i under a given oil price scenario and a given CO2 quota price scenario [MNOK]
PROF_OPT: dynamic array(states, nodes, periods)of real       !Optimal accumulated profit from t until T given oil price and CO2 scenario when being in state i in period i [MNOK]
E_PROF_OPT: dynamic array(states, nodes,periods)of real      !Expected optimal accumulated profit from t+1 and out time horizon [MNOK]
BEST: dynamic array (states, nodes, periods)of integer       !Optimal choice of state for period t+1, when standing in state i in period t, given oil and CO2 price scenarios [-]

NODE_PERIOD_LOGIC: dynamic array(nodes, periods) of real     !=1 if it is possible to be in this price state in this time period [-]
NODE_TRANS_PROB: dynamic array(nodes, nodes) of real         !Gives the transition probability of going from node i to node j. Equals 0 if no transition is possible [-]
CUM_NODE_TRANS_PROB: dynamic array (nodes,nodes) of real     !The cumulative transition probability [-]

SIM_PRICE_OIL: array (simulations, periods) of real          !Simulated oil price in period p in simulation s [MNOK/barrel]
SIM_PRICE_CO2: array (simulations, periods) of real          !Simulated co2 price in period p in simulation s [MNOK/MTonne]
SIM_NODE: array (simulations, periods) of integer            !The price-node in period p in simulation s [-]
DECISION: array (simulations, periods) of integer            !The best state to go to in the next period in simulation s - taken from the stochastic dymamic program [-]

end-declarations

!#####################################################################################################
!MAIN INITIALIZATIONS
initializations from "mmodbc.odbc:data_for_model.xls"
```

```
FLOW as "Flow"
r as "Disc"
INFL as "Infl"
STD_CO2 as "STD_CO2"
STD_OIL as "STD_OIL"
DT as "DT"
CORR as "CORR"
PROG_OIL as "PROG_OIL"
PROG_CO2 as "PROG_CO2"
A_2D as "A_logic"
PROB as "PROB"

OPEX_FACTOR as  "OPEX_FACTOR"
REV_FACTOR as "REV_FACTOR"
CAPEX_FACTOR as "CAPEX_FACTOR"

TOT_OIL_PRODUCE as "TOT_OIL_PRODUCE"
EOR_RATE as "EOR_RATE"

I_CAPT_20 as "I_CAPT_20"
I_CAPT_40a as "I_CAPT_40a"
I_CAPT_40b as "I_CAPT_40b"
OPEX_CAPT  as  "OPEX_CAPT"

I_SEP_20 as "I_CAPT_20"
I_SEP_40a as "I_CAPT_40a"
I_SEP_40b as "I_CAPT_40b"
OPEX_SEP as "OPEX_CAPT"


I_ALLPIPES  as  "I_ALLPIPES"
OPEX_PIPES as "OPEX_PIPES"
```

```
I_STORAGE as "I_STORAGE"
OPEX_STORAGE as "OPEX_STORAGE"

I_EOR as "I_EOR"
OPEX_EOR as "OPEX_EOR"

end-initializations

!################################################################################

!CALCULATION OF GENERAL VALUES:

!Making the state transition logic 3D:

forall(p in 1..P-1,s1,s2 in states) do
A_3D(s1,s2,p):=A_2D(s1,s2)


        !TIME WINDOWS FOR EOR:
        !Not possible to have operation of EOR (state 8,9,10) before 2015


        !It is not possible to go from state 9 to 10 in years before 2016 and after 2023:
                if (p<9 OR p>16) then
                A_3D(9,10,p):=0
        end-if

        !It is not possible to go from state 8 to 9 in years before 2015 and after 2022:
        if (p<8 OR p>15) then
                A_3D(8,9,p):=0
        end-if

        !It is not possible to go from state 7 to 8 in years before 2014 and after 2021:
        if (p<7 OR p>14) then
```

```
		A_3D(7,8,p):=0
	end-if

	!It is not possible to go from state 6 to 7 in years before 2013 and after 2020:
	if (p<6 OR p>13) then
		A_3D(6,7,p):=0
	end-if

	!It is not possible to go from state 4 to 7 in years before 2014 and after 2021:
	if (p<6 OR p>13) then
		A_3D(4,7,p):=0
	end-if

	!It is not possible to go from state 6 to 6 in years earlier than 2012 (period 4)
	if p<5 then
		A_3D(6,6,p):= 0
	end-if

	!!It is not possible to go from state 5 to 8 in years before 2015 and later than 2022
	if (p<7 OR p>14) then
		A_3D(5,8,p):=0
	end-if

	!It is not possible to go from state 3 to 5 in years before 2014 and later than 2021
	if (p<6 OR p>13) then
		A_3D(3,5,p):=0
	end-if

end-do

!#####################################################################################
!CALCULATION OF VALUES FOR STOCHASTICS:

!Calculation of values for the recombining nonrectangular tree (3D)
```

```
!Slopes (from price forecasts)
        SLOPE_CO2:= (PROG_CO2(P+1)/PROG_CO2(1))^(1/(P+1))-1
        SLOPE_OIL:= (PROG_OIL(P+1)/PROG_OIL(1))^(1/(P+1))-1

!Up and down factor for oil
        UP:= exp((SLOPE_OIL - (STD_OIL^2)/2)*DT + STD_OIL*sqrt(DT) )
        DOWN:= exp((SLOPE_OIL - (STD_OIL^2)/2)*DT - STD_OIL*sqrt(DT) )

!Correlation-adjusted up and down factors for CO2
        A:= exp((SLOPE_CO2 - (STD_CO2^2)/2)*DT + STD_CO2*sqrt(DT)*(CORR+sqrt(1-CORR^2)) )
        B:= exp((SLOPE_CO2 - (STD_CO2^2)/2)*DT + STD_CO2*sqrt(DT)*(CORR-sqrt(1-CORR^2)) )
        C:= exp((SLOPE_CO2 - (STD_CO2^2)/2)*DT - STD_CO2*sqrt(DT)*(CORR-sqrt(1-CORR^2)) )
        D:= exp((SLOPE_CO2 - (STD_CO2^2)/2)*DT - STD_CO2*sqrt(DT)*(CORR+sqrt(1-CORR^2)) )

!Initializing the logic for which node (comb of CO2- and oilprice) that exist in the various time periods
k:=0
forall(p in periods) do
        k:=sum(j in 1..p-1)j*j
                forall(i in 1..p*p)
                        NODE_PERIOD_LOGIC(k+i,p):=1      !It is possible to be in node (k+i) in time p
end-do

!The prices in the start node has to equal the forecasted prices in the first time period
PRICE_OIL(1):= PROG_OIL(1)
PRICE_CO2(1):= PROG_CO2(1)

!Algorithm for creating transition probabilites between
!price nodes and their values in the pyramid shaped 3D-tree
forall(p in periods) do

        N_p_1:=sum(s in 1..p-1)(s*s)        !Accumulated number of nodes including period p-1:
        N_p:=N_p_1+p*p                      !Accumulated number of nodes including period p:

        forall(q in 1..p | p < P)do
```

```
                    forall(i in 1..p)do
                    NODE_TRANS_PROB(N_p_1+(q-1)*p+i, N_p+(q-1)*(p+1)+i):=PROB
                    NODE_TRANS_PROB(N_p_1+(q-1)*p+i, N_p+(q-1)*(p+1)+i+1):=PROB
                    NODE_TRANS_PROB(N_p_1+(q-1)*p+i, N_p+q*(p+1)+i):=PROB
                    NODE_TRANS_PROB(N_p_1+(q-1)*p+i, N_p+q*(p+1)+i+1):=PROB

                    PRICE_OIL(N_p+(q-1)*(p+1)+i+1):=UP*PRICE_OIL(N_p_1+(q-1)*p+i)
                    PRICE_CO2(N_p+(q-1)*(p+1)+i+1):=B*PRICE_CO2(N_p_1+(q-1)*p+i)
                    PRICE_OIL(N_p+q*(p+1)+i):=DOWN*PRICE_OIL(N_p_1+(q-1)*p+i)
                    PRICE_CO2(N_p+q*(p+1)+i):=C*PRICE_CO2(N_p_1+(q-1)*p+i)
                    PRICE_OIL(N_p+q*(p+1)+i+1):=DOWN*PRICE_OIL(N_p_1+(q-1)*p+i)
                    PRICE_CO2(N_p+q*(p+1)+i+1):=D*PRICE_CO2(N_p_1+(q-1)*p+i)
                    PRICE_OIL(N_p+(q-1)*(p+1)+i):=UP*PRICE_OIL(N_p_1+(q-1)*p+i)
                    PRICE_CO2(N_p+(q-1)*(p+1)+i):=A*PRICE_CO2(N_p_1+(q-1)*p+i)
                    end-do
          end-do
end-do


! Calculate the cumulative probability density (to be used in the simulation)

forall(n in nodes) do
k:=1
          forall(n2 in nodes|NODE_TRANS_PROB(n,n2)>0)do
                    CUM_NODE_TRANS_PROB(n,n2) := NODE_TRANS_PROB(n,n2)*k
                    k:=k+1
          end-do
end-do


!##############################################################################################
!INITIALIZING MATRICES

!Setting the value of EXTRA_OIL:
```

```
years:=14                                                                                                                         !14 represents the maximum amount of years we have income from EOR
forall(p in periods | p>7 AND p<16) do
        EXTRA_OIL(p+1):=TOT_OIL_PRODUCE*EOR_RATE/years
        years:=years-1
end-do

!Initializing operational costs
forall(s in states, n in nodes, p in periods) do
        O(1,s,n):=OPEX_FACTOR(1,s)*PRICE_CO2(n)*FLOW
        O(2,s,n):=OPEX_FACTOR(2,s)*OPEX_CAPT
        O(3,s,n):=OPEX_FACTOR(3,s)*OPEX_PIPES
        O(4,s,n):=OPEX_FACTOR(4,s)*OPEX_EOR
        O(5,s,n):=OPEX_FACTOR(5,s)*OPEX_SEP
end-do

!Initializing investment costs
forall(s in states, p in periods) do
        I(1,s,p):= CAPEX_FACTOR(1,s)*I_CAPT_20(p)
        I(2,s,p):= CAPEX_FACTOR(2,s)*I_CAPT_40a(p)
        I(3,s,p):= CAPEX_FACTOR(3,s)*I_CAPT_40b(p)
        I(4,s,p):= CAPEX_FACTOR(4,s)*I_ALLPIPES
        I(5,s,p):= CAPEX_FACTOR(5,s)*I_EOR
        I(6,s,p):= CAPEX_FACTOR(6,s)*I_STORAGE
        I(7,s,p):= CAPEX_FACTOR(7,s)*OPEX_STORAGE
        I(8,s,p):= CAPEX_FACTOR(8,s)*I_SEP_20(p)
        I(9,s,p):= CAPEX_FACTOR(9,s)*I_SEP_40a(p)
        I(10,s,p):= CAPEX_FACTOR(10,s)*I_SEP_40b(p)
end-do

!#######################################################################################
!ASSIGNING START AND END VALUES

!Start values in matrices that are to be caclulated in the model.Fictional values
forall(p in 1..P-1, n in nodes, i in states | NODE_PERIOD_LOGIC(n,p)=1) do
```

```
		BEST(i,n,p):= 200
		PROF_OPT(i,n,p):= -999999999999999999999999
end-do

!Assign future profits for the different states in the end time period
!Note: the future profit for state 10 in the last period is calculated later (dependent on the start-year of EOR)

forall(s1,s2 in states, n in nodes|
		NODE_PERIOD_LOGIC(n,P)=1 AND A_3D(s1,s2,P-1)=1 AND s2 <> 10)do
				PROF(s2,n,P):=
				-(sum(rc in rows_capex)I(rc,s2,P))*(1+INFL)^(P-1)   -
				(sum(ro in rows_opex)O(ro,s2,n) )*(1+INFL)^(P-1)
end-do


!Set all final values of PROF_OPT to the value of PROF in final time period:
forall(i in states, n in nodes)
		PROF_OPT(i,n,P):=PROF(i,n,P)


!##############################################################################
!THE STOCHASTIC DYNAMIC PROGRAM
!Calculate the future profits in all states, for all possible transitions

!NOTE:	State 9 and 10 have to be separated from the other states because
!				the profits are dependent on the start year of EOR


!STATE 10: The BEST state transition from 10 will always be 10
forall (n in nodes, p in periods|NODE_PERIOD_LOGIC(n,p)=1)
				BEST(10,n,p) := 10

! STATE 9: Backward programming
forall(p in 1..(P-1))do
```

```
!Entering only if it is possible to go from 9 to 10 in this time period
if A_3D(9,10,(P-p))=1 then

      forall(n in nodes|NODE_PERIOD_LOGIC(n,P)=1)do
                  PROF_OPT(10,n,P):=
                  (-(sum(rc in rows_capex)I(rc,10,P)) +
                  (sum(rr in rows_rev)REV_FACTOR(rr,10)*PRICE_OIL(n)* EXTRA_OIL(P-p)) -
                  (sum(ro in rows_opex)O(ro,10,n) ))*(1+INFL)^(P-1)
      end-do
      !Calculating the expected profit for state 10 in all time periods after the present state (T-p) to T
      forall(ti in 1..p) do
            forall(n in nodes | NODE_PERIOD_LOGIC(n,P-ti)=1) do

                  E_PROF_OPT(10,n,P-ti+1):= sum(n2 in nodes |
                  NODE_TRANS_PROB(n,n2)>0) NODE_TRANS_PROB(n,n2)*PROF_OPT(10,n2,P-ti+1)

                  PROF_OPT(10,n,P-ti):=
                  (-(sum(rc in rows_capex)I(rc,10,P-ti)) +
                  (sum(rr in rows_rev)REV_FACTOR(rr,10)*PRICE_OIL(n)* EXTRA_OIL(P-p))-
                  (sum(ro in rows_opex)O(ro,10,n)))*(1+INFL)^(P-ti-1) +
                  (1+r)^(-1)*E_PROF_OPT(10,n,P-ti+1)
            end-do
      end-do

      forall(n in nodes | NODE_PERIOD_LOGIC(n,P-p)=1 )do
            !Calculating the expected profit from t and out horizon, for state 9:

            PROF(9,n,P-p):=
            (-(sum(rc in rows_capex)I(rc,9,P-p)) -
            (sum(ro in rows_opex)O(ro,9,n)))*(1+INFL)^(P-p-1)  +
            (1+r)^(-1)*E_PROF_OPT(10,n,P-p+1)

            !Forcing the optimal profit to be the only profit we have calculated:
```

```
                PROF_OPT(9,n,P-p):=PROF(9,n,P-p)

                !This optimal profit is generated from the only possible state transition 9-10:
                BEST(9,n,P-p):=10
            end-do
        end-if
end-do


!STATE 1-8: Backward programming
forall( p in 1..(P-1)) do
        forall(i in states, n in nodes|
        NODE_PERIOD_LOGIC(n,P-p)=1  AND i < 9) do
            !Check every possible way to go (j) and update the PROF_OPT:
            forall(j in states |A_3D(i,j,P-p)=1) do
                !Calculating the future expected profit from time t+1 and out horizon
                E_PROF_OPT(j,n,P-p+1):= sum(n2 in nodes |
                NODE_TRANS_PROB(n,n2)>0 ) NODE_TRANS_PROB(n,n2)*PROF_OPT(j,n2,P-p+1)

                !Calculating the expected profit from t and out horizon
                PROF(i,n,P-p):=
                (-(sum(rc in rows_capex)I(rc,i,P-p)) -
                (sum(ro in rows_opex)O(ro,i,n) ))*(1+INFL)^(P-p-1)  +
                (1+r)^(-1)*E_PROF_OPT(j,n,P-p+1)

                !Save the incumbent best profit in a matrix:
                if(PROF(i,n,P-p)>PROF_OPT(i,n,P-p)) then
                    PROF_OPT(i,n,P-p):=PROF(i,n,P-p)
                    !Save the according best state transition, generating this opt.profit
                    BEST(i,n,P-p):=j
                end-if
            end-do
        end-do
end-do
```

```
!##############################################################################################
! MONTE CARLO SIMULATION - THE INVERSE TRANSFORM

forall (s in simulations, p in 1..P-1) do
        if p=1 then
                k:=1
                SIM_NODE(s,p):=k

        end-if

        randomvar:=random

        forall (n in nodes|
                NODE_TRANS_PROB(k,n)>0 AND NODE_PERIOD_LOGIC(n,p+1)=1)do
                if (CUM_NODE_TRANS_PROB(k,n)> randomvar) then
                                k:=n
                                SIM_NODE(s,p+1):=k
                break                                   !Break if CUM_NODE_TRANS_PROB > randomvar
                end-if
        end-do
end-do

!########################################################################################################
!The optimal investment decisions for each of the simulations

forall(s in simulations) do
        forall (p in 1..P-1 )do
                if p=1 then
                        DECISION(s,p):=BEST(1,1,1)
                else
                        DECISION(s,p):=BEST(DECISION(s,p-1), SIM_NODE(s,p), p)
                end-if
        end-do
end-do
```

```
forall(s in simulations) do

        forall(p in 2..P)do
                if DECISION(s,p-1)=10 then
                        EXTRA(s):=EXTRA_OIL(p-1)
                break
                end-if
        end-do

        forall (p in periods) do
        if p=1 then
                NPV(s,p):= (-(sum(rc in rows_capex)I(rc,1,p)) -
                (sum(ro in rows_opex)O(ro,1,1) ))*(1+INFL)^(p-1)

        else
                if DECISION(s,p-1)=10 then
                        NPV(s,p):= (-(sum(rc in rows_capex)I(rc,DECISION(s,p-1),p)) +
                        (sum(rr in rows_rev)REV_FACTOR(rr,DECISION(s,p-1))*PRICE_OIL(SIM_NODE(s,p))* EXTRA(s)) -
                        (sum(ro in rows_opex)O(ro,DECISION(s,p-1),SIM_NODE(s,p)) ))*(1+INFL)^(p-1)

                else
                        NPV(s,p):=(-(sum(rc in rows_capex)I(rc,DECISION(s,p-1),p)) -
                        (sum(ro in rows_opex)O(ro,DECISION(s,p-1),SIM_NODE(s,p)) ))*(1+INFL)^(p-1)

                end-if
        end-if
        end-do

end-do


!##############################################################################################

end-model
```